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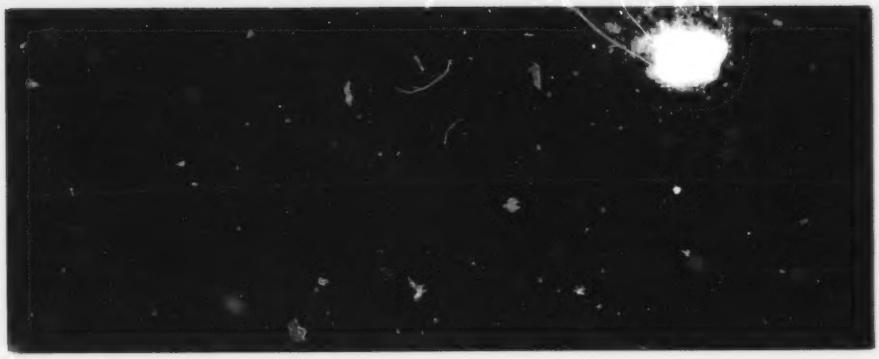

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Effects of Heating the Inlet Air With a Burner When Natural Air Drying

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EFFECTS OF HEATING THE INLET AIR WITH A BURNER WHEN NATURAL AIR DRYING

FINAL REPORT

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March, 1987

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Final Report

August, 1986, to March, 1987

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ABSTRACT

EFFECT OF HEATING THE INLET AIR WITH A BURNER WHEN NATURAL AIR DRYING

ADF Project R-86-02-0117

Natural air drying without heat was more economical than with heat in the early fall. In late fall, drying costs by both methods were nearly equal but higher than in the early fall. Thus, harvest and drying strategy should attempt to complete all drying in early fall using natural air.

If harvest is delayed to late fall, natural air drying or adding supplemental heat can be used as costs were similar. However, if adding supplemental heat, the chance of completing drying in the fall was very good. Conversely, drying would likely have to be completed in the spring if using natural air.

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1. INTRODUCTION

During the falls of 1985 and 1986, the cool and humid harvest weather conditions seriously reduced the performance of natural air drying systems. This prompted many farmers to consider adding supplemental heat when natural air drying. Claimed benefits were reduced humidity and increased temperature of the air, allowing drying to continue regardless of the weather. With drying completed before winter, the grain would be available for sale and no winter supervision would be required. Apparent disadvantages of adding heat included increased cost, increased overdrying, and the possibility of spoilage from condensation inside the bin roof.

This research was conducted to investigate the implications and to develop recommendations about adding supplemental heat to natural air drying. Different supplemental heat strategies were compared to natural air drying in field tests at the PAMI grain dryer test facility.

The drying time, energy consumption, and drying costs while adding supplemental heat depend on the grain moisture content, weather conditions, fuel costs, and grain market value. The influence of these variables were investigated with grain drying simulation models.

2. OBJECTIVES

Objectives of these tests were to:

1. Conduct field tests to compare the drying time, energy consumption, quality of work, and ease of operation with different supplemental heat strategies.

2. Develop a computer model to simulate adding supplemental heat during natural air drying. Verify the simulation by comparing the results predicted by computer simulation to results obtained in the field tests for each drying strategy.
3. Use the verified simulations to thoroughly compare different heating strategies, develop recommendations, and draw conclusions.

3. SUMMARY AND CONCLUSIONS

FIELD TESTING

Adding heat decreased drying times compared to natural air drying without heat. Adding a lot of heat reduced drying time considerably when average drying. Drying with inlet air temperatures heated to 104°F (40°C) and 86°F (30°C) resulted in drying times that were 78 and 54% less than natural air drying without heat.

In unfavorable weather for natural air drying, adding as little as 9 to 18°F (5 to 10°C) heat permitted drying to continue at a rate slightly faster than natural air drying in favorable weather. Natural air drying without heat in unfavorable weather did not progress in some conditions. When "through drying"* while adding heat, the percentage of decreased drying time was not as great as when "average drying". In humid and cool weather, there was little difference in drying time between adding a little heat continuously or adding a little heat only when the outside humidity was high.

Adding heat consumed more energy than when natural air drying without heat. Even though adding heat reduced drying time, the fuel

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Terminology is defined in APPENDIX I.

energy was a larger component than the electrical energy, hence the total energy increased even though drying time decreased. The highest energy consumption occurred when the most heat was added. Of the different adding heat strategies, highest energy consumption occurred when the inlet air temperature was heated to 104°F (40°C), while lowest energy consumption occurred when the heater was only operated if relative humidity exceeded 70%. In adverse weather, when natural air drying or adding heat, more energy was consumed than by a hot air dryer. Also, "through drying" consumed much more energy than "average drying".

Overdrying increased as the amount of added heat was increased. It was very important to "average dry" and mix the bin when adding a lot of heat. When heating the inlet air temperature to 104°F (40°C) and "through drying", the average bin moisture content was only 7%. The amount of overdrying decreased dramatically when heat was only added if the relative humidity exceeded 70%.

No grade loss occurred from any treatment. However, condensation on the inside of the bin roof occurred when the inlet air temperature was held at 104°F (40°C). Condensation will reduce drying rate. More importantly, it wet the upper grain surface and led to some spoilage.

Labour requirements were about the same whether adding heat or not. When adding heat, monitoring had to be performed more often but over a shorter time period. Heater controls reduced supervision.

Installation of the heater was easy. It was important to calibrate the heater controls as some scales may not be accurate. No servicing was required during the tests.

SIMULATION MODEL DEVELOPMENT

Computer programs were developed to simulate natural air drying with various "adding heat" strategies with real weather data. The computer simulations were verified by comparing them to the experimental data collected during field tests.

When comparing drying times under similar conditions, the programs predicted the drying time within 20% of the experimental values. Predicted energy consumption was higher than the experimental values. This likely occurred because the field test airflow rates were quite high. At more typical airflow rates, the predicted energy consumption appeared to be quite accurate. Quality models were in their infancy stage. They were investigated, but they did not correlate well with field test results. It was decided not to use them. Cost models used well established principles so only entry accuracy was verified with hand checks.

It was concluded that the developed simulation models were sufficiently accurate to be used for detailed performance and economic analysis of the different strategies.

COMPUTER SIMULATION RESULTS

The effect of five variables on the drying time were investigated. The drying time increased as initial moisture content increased, as the amount of added heat decreased, when the start date was delayed, when the airflow rate decreased, and if "through drying" instead of "average drying". When natural air drying with 1 cfm/bu (13 L/s.m^3) in September, the drying time increased by 108% (from 15.7 to 32.7 days) as initial moisture content increased from 16 to 22%. For the same conditions, when adding 18°F (10°C),

the respective drying times increased by 216% (from 4.2 to 13.3 days). As start date was delayed from August 1 to October 1 for the same airflow rate while adding 9°F (5°C), drying time increased by 61% (from 10.7 to 17.2 days). When airflow rate was decreased from 2.0 to 0.5 cfm/bu (26 to 7 L/s.m^3) while adding the same heat in August, drying time increased by 359% (from 3.2 to 14.7 days). When "through drying" from 19% and adding 9°F (5°C) in September, the drying time was 120% more than when "average drying".

Energy consumption increased as initial moisture content increased, as the amount of added heat was increased, and as the start date was delayed. When natural air drying with 1 cfm/bu (13 L/s.m^3) in September, energy consumption increased by 107% [from 1,520 to 3,160 Btu/bu (59 to 123 MJ/t)] as initial moisture content increased from 16 to 22%. For the same condition when adding 18°F (10°C), the respective energy consumption increased by 213% [from 2,410 to 7,540 Btu/bu (94 to 294 MJ/t)]. As start date was delayed from August 1 to October 1 for the same airflow rate while adding 9°F (5°C), energy consumption increased by 60% [from 3,540 to 5,670 Btu/bu (138 to 221 MJ/t)].

Quality models did not provide relevant results. However, the field test results indicated that no quality reduction occurred from any treatment. Quality of the respective systems was also rated by the overdrying that occurred. If the bin was "through dried", overdrying will occur. Although initial moisture content and start date have some effect, the amount of added heat was the main factor. In some cases, 6% overdrying occurred.

The capital costs were the largest component of drying cost. Thus, strategies that minimized capital costs were typically the least expensive.

The drying costs increased as initial moisture content increased, as the amount of added heat decreased, as the start date was delayed, and if "through drying" instead of "average drying". When natural air drying at 1 cfm/bu (13 L/s.m^3) in September, the drying costs increased by 38% [from 16 to 22¢/bu ($5.88 to $8.08/t)] as initial moisture content increased from 16 to 19%. The increase of only 6¢/bu ($2.20/t) was small considering five times as much moisture was being removed. If there are advantanges related to high moisture harvesting, the small increase in drying costs at higher moisture contents may also promote them. When adding 18°F (10°C) for the same drying conditions as above, the respective drying costs were 18 to 29¢/bu ($6.61 to $10.66/t). Other simulated strategies of adding less heat were more expensive. This is likely because when using a heater, minimizing the operating time will minimize the associated capital cost component, which is the largest component of total cost.

As the start date was delayed from August 1 to October 1 when natural air drying from 19% with 1 cfm/bu (13 L/s.m^3), the drying costs increased by 56% [from 16 to 25¢/bu ($5.88 to $9.19/t)]. This promotes the benefits of harvesting and drying early, even though the grain may be at higher moisture contents. The cost to dry later in the year was more than the cost to dry from higher moistures. "Through drying" the grain, instead of "average drying", increased all drying costs considerably. With the various adding heat

strategies, drying costs ranged from as much as 40 to 75¢/bu ($14.70 to $27.55/t). These costs make "through drying" totally uneconomical.

No constant relationship existed between airflow rate and drying costs as other conditions such as start date and adding heat strategy all had interrelated effects. In August, airflow rate had little effect on cost. Natural air drying was cheaper than adding heat. In October, natural air drying cost increased with airflow rate, while adding heat cost decreased with airflow rate. At the typical airflow rate of 1 cfm/bu (13 L/s.m^3), the drying costs of natural air drying and adding 18°F (10°C) were similar.

4. RECOMMENDATIONS

From the results of this project, certain recommendations have emerged to obtain the maximum performance from natural air drying at the minimum drying cost. For operators of natural air drying systems, PAMI recommends:

1) Natural air drying fans and equipment should be sized to deliver at least 1 cfm/bu (13 L/s.m^3) to provide acceptable drying times. Higher airflow rates can be used to speed up drying as they are only a bit more costly than 1 cfm/bu (13 L/s.m^3), but the fan size increase may cause the farm electrical capacity to be exceeded.
2) Harvesting of cereals should begin as early in the fall as crop moisture reaches 20% to permit natural air drying to begin in the early fall.

3) When drying is delayed into poor drying conditions, typical of October, farmers can either continue using natural air drying which will likely require spring drying or use a heater which will complete drying in the fall. Economically, both options are similar so the selection should best suit the specific situations.

4) Outside air temperature should be the main guide for the time to start adding heat, although relative humidity, location, and calendar date may also affect the decision. Heaters should be used if drying is not completed before the outside night temperatures drop into the 41 to 32°F (5 to 0°C) range. In Saskatoon area, a typical date to consider adding heat is about October 1, unless the bin is nearly dry. However, outside temperatures should be the main guideline. Heaters can also be used in warm weather if the relative humidity exceeds 70% for extended periods.

5) Heaters should be typically set to add 18°F (10°C). Outside air temperatures should be monitored and if they drop or increase greatly, the temperature rise may have to be adjusted. Heated air temperatures should not exceed 77°F (25°C) or drop below 41°F (5°C) for extended periods. A temperature control can reduce the supervision.

6) If weather conditions turn very cold, heaters may have to be shut down and drying completed in the spring. If the inlet air temperature cannot be held to at least 41 to 50°F (5 or 10°C), the heater should be shut off.

7) Operators should only purchase the minimum number of heaters required to complete drying in the fall.

8) Natural gas heaters should only be used if the cost of installation is minimal, as it only decreases energy drying cost by 2 to 3¢/bu ($0.73 to $1.10/t).

9) After the bin is "average dry", the heater should be shut off until the grain is cooled and then the grain should be mixed. "Through drying" is very uneconomical and should be avoided, especially when adding heat.

5. LITERATURE REVIEW

Because adding small amounts of supplemental heat is a relatively new drying strategy on the prairies, not much applicable research has been done on this topic. Johnson and Otten (1979) recommended that supplemental heat should be available when the relative humidity of the air rises to a point where drying is prevented for periods of 24 hours or more.

Fraser and Muir (1980) studied energy savings using natural air drying and the use of solar collectors that added 9°F (5°C) and 18°F (10°C). They simulated wheat drying in Winnipeg, Swift Current, and Edmonton and showed that solar energy reduced energy consumption to dry grain and increased the probability of drying. An airflow rate of at least 1.2 cfm/bu (15.6 L/s.m^3) was needed to dry grain with natural air in Swift Current. Airflow rates of 1.8 and 3 cfm/bu (23.4 and 39 L/s.m^3) were necessary in Edmonton and Winnipeg, respectively. However, recent publications by the provincial Agriculture Departments indicate that lower airflow rates are being used successfully.

Muhbauer et al. (1982) compared the following five low temperature in-bin drying procedures to dry wheat in West Germany:

(1) continuous fan operation pushing air through the grain mass,

(2) continuous fan operation pulling air through the grain mass,

(3) fan off when relative humidity of air was more than 70 percent,

(4) continuous fan with heat added to reduce relative below 70 percent (humidistat),

(5) continuous operation of the fan with constantly pre-heated air by 9°F (5°C).

The bins were 6 ft (1.8 m) diameter and 13 ft (4 m) high. The airflow rate used was 1.5 cfm/bu (19.5 L/s.m^3). The initial moisture content ranged from 19.4 percent in bin (2) to 23.4 percent in bin (5). Ranking by fastest to the slowest drying rate was a follows: (5), (4), (2), (1), (3). Ranking by energy efficiency was as follows: (3), (2), (1), (4), (5). None of the methods showed any significant decreases in the grain quality. The highest risk for mold and dry matter loss was bin (3) in which the humidistat was used. Continuous fan operation (1) proved to be the best overall method followed by continuously adding heat to the air (5).

It was clear that further research was required to develop up-to-date recommendations for adding supplemental heat when natural air drying in Saskatchewan.

6. FIELD TESTING

6.1 SCOPE OF TEST

6.1.1 Test Equipment: All field tests were performed at the PAMI grain dryer test facility in Humboldt, Saskatchewan.

One Westeel-Rosco model 146 and two model 148 flat-bottom bins, capable of holding about 1710 bu (57.6 m^3), were used for all drying tests. All three bins were equipped with fully perforated raised floors, and Caldwell 3 hp (2.2 kW), 24 in (609 mm), model ILC 24-312, in-line centrifugal natural air drying fans (FIGURE 1). The two model 148 bins were also equipped with Caldwell model ILCH 24-VPGE natural air drying supplemental heaters. These heaters were propane fueled and were equipped with humidistat and thermostat controllers.

The PAMI grain dryer test facility, consisting of four bins, with a combined storage capacity of 15,000 bu (550 m^3), high capacity conveying equipment to handle grain up to 2500 bu/h (90 m^3/h), and various other support equipment, was used for grain handling and test measurements.

Detailed specifications of the fans, heaters, and bins are given in APPENDIX I.

6.1.2 Test Procedures: Field tests took place during the fall of 1986. About 5130 bu (140 t) of Canada No. 1 CW red spring wheat with 1% dockage was artificially wetted to 17.5% moisture content. The wheat was divided into three batches, placed into each of the three drying bins, and dried until the drying front passed through the top of the grain mass (through dried).

FIGURE 1. Fan and Heater.

Test conditions and supplemental heat drying strategies are given in TABLES 1 to 3.

TABLE 1. Run 1 Test Conditions.

TEST MONTH - August		
WEATHER CONDITIONS - Normal Harvest Weather		
	DRYING STRATEGY	GRAIN QUANTITY bu (t)
BIN A	Inlet Air Temperature Held at 104°F (40°C)	1720 (46.8)
BIN B	Inlet Air Temperature Held at 86°F (30°C)	1700 (46.2)
BIN C	Standard Bin (no heat added)	1650 (44.9)

TABLE 2. Run 2 Test Conditions.

TEST MONTH - September		
WEATHER CONDITIONS - Wet and Rainy (High Humidity)		
	DRYING STRATEGY	GRAIN QUANTITY bu (t)
BIN A	Add 9°F (5°C) if Relative Humidity Above 70%	1750 (47.6)
BIN B	Add 18°F (10°C) Above Ambient Temperature	1710 (46.5)
BIN C	Standard Bin (no heat added)	1710 (46.5)

TABLE 3. Run 3 Test Conditions.

TEST MONTH - October		
WEATHER CONDITIONS - Favorable at Start, Turning to Cold (Below Freezing) and Snow at End		
	DRYING STRATEGY	GRAIN QUANTITY bu (t)
BIN A	Add 14°F (8°C) if Relative Humidity above 70%	1730 (47.1)
BIN B	Add 18°F (10°C) Above Ambient Temperature	1710 (46.5)
BIN C	Standard Bin (no heat added)	1720 (46.8)

6.1.3 Test Measurements: Grain samples were collected from each bin at various depths as soon as the grain was loaded into the bin and at periodic intervals during drying. Grain samples were obtained by inserting a grain probe through a probe port in the side of the bin.

Moisture content was determined with a Dickey-John capacitance moisture meter calibrated against an air oven, and grain quality was assessed by the Canadian Grain Commission. Propane consumption was measured by monitoring the propane tank weight during drying, and electrical energy consumption of the natural air drying fans was measured using a wattmeter. Grain and ambient temperatures were measured using thermocouples and recorded using a Sciemetric Instruments model 8082A electronic measurement system.

Static pressure at the natural air drying fan outlet was recorded at the beginning and ending of each drying cycle. Static pressure was related to a fan performance chart to determine airflow. Actual airflow was also measured to verify the static pressure measurements. The fan performance chart had been developed by PAMI. Grain mass was measured using a bin mounted on four load cells.

6.1.4 Treatment of Data: In any field testing, it is difficult to keep test conditions consistent, especially when tests are conducted at different times of the year. To provide a meaningful relationship between all tests, results have been mathematically adjusted to the conditions given in TABLE 4.

TABLE 4. Adjusted Operating Conditions.

1.	Grain Quantity - 1710 bu (46.5 t)
2.	Moisture Content - Initial - 17.5% - Final - 14.5%
3.	Airflow Rate - 1.8 cfm/bu (23 L/s.m^3)

All grain quantities have been adjusted to 14.5% moisture content based on the amount of dry matter present.

Initial and final moisture contents from the grain were adjusted according to the drying characteristics of each individual bin. Due to unfavourable weather conditions, the standard bin (Bin C) in Runs 2 and 3, did not completely dry in the allocated test period. For a valid comparison, the drying times for these runs had to be extrapolated to the required time to complete drying. This was done by adding the measured drying time to the calculated time to complete drying under appropriate conditions. For Run 2, the calculated drying time was determined using the drying rate in Run 1 since a warm period occurred after the Run 2 shutdown. This warm period had similar conditions to Run 1. For Run 3, the calculated drying time was determined from the drying rate in a spring drying test on another project (Lischynski, 1987), since no further drying weather occurred in the fall after the Run 3 shutdown.

Because the airflow rates were not exactly equal in all tests, all natural air drying times were adjusted to a standard condition of 1.8 cfm/bu (23 L/s.m^3). It was assumed that drying time was inversely proportional to airflow rate.

6.2 DRYING TIME

Drying times for all three bins in all three runs are shown in TABLE 5.

TABLE 5. Drying Times for Average Drying.

	RUN 1 (August)		RUN 2 (September)		RUN 3 (October)	
	CONDITION	DRYING TIME days	CONDITION	DRYING TIME days	CONDITION	DRYING TIME days
BIN A	104°F (40°C) Inlet Air Temperature	3.0	Add Heat if Humidity > 70%	9.5	Add Heat if Humidity > 70%	10.6
BIN B	86°F (30°C) Inlet Air Temperature	6.3	Add 18°F (10°C) Above Ambient Temperature	10.1	Add 18°F (10°C) Above Ambient Temperature	9.0
BIN C	Standard Bin (Normal Weather)	13.8	Standard Bin (Humid Weather)	30.6*	Standard Bin (Cold Weather)	29.4**

* Consists of 24.2 test days to dry to 15.8% plus 6.4 calculated days to complete drying later in the fall.

** Consists of 18.9 test days to dry to 16.0% plus 10.5 calculated days to complete drying in the spring.

The Run 1 results showed that increasing the amount of added heat to natural air drying reduced drying time considerably. Drying time in Bin A [104°F (40°C) inlet air temperature] was 3.0 days, compared to 6.3 days in Bin B [86°F (30°C) inlet air temperature], and 13.8 days in Bin C (standard bin). This suggested that drying with high inlet air temperatures (by adding large amounts of heat) was desirable, as it resulted in decreased drying time. However, drying time is not the only consideration when choosing a drying strategy.

Runs 2 and 3 both exhibited the benefits of adding smaller amounts of supplemental heat during adverse weather conditions. During both of these runs, the weather was unfavourable for natural air drying, so the standard bin did not complete drying until 30.6 and 29.4 days of operation in Runs 2 and 3, respectively. However,

in both of these runs, Bins A (add heat if above 70% R.H.) and B [add 18°F (10°C) above ambient] dried in 9.0 to 10.6 days. Not only did the grain completely dry in unfavourable weather, but drying was completed in less time than natural air drying took during favourable weather (Bin C, Run 1). This suggests that in unfavourable weather, adding a small amount of heat, using either of the drying strategies, will allow drying to continue and possibly be completed in less time than normal natural air drying.

In Runs 2 and 3, drying times for Bins A and B were very similar, even though drying stategies were different. This seems logical in this case, because of the weather conditions during the tests. Humid conditions during both Runs 2 and 3 caused the Bin A heater to run almost constantly, which was comparable to the Bin B heater, which was running constantly, and adding similar amounts of heat.

The above conclusions were all based on drying the bins to "average dry". Drying times for all three bins in all three runs for "through drying" are given in TABLE 6.

TABLE 6. Drying Times for Through Drying.

	RUN 1 (August)		RUN 2 (September)		RUN 3 (October)	
	CONDITION	DRYING TIME days	CONDITION	DRYING TIME days	CONDITION	DRYING TIME days
BIN A	104°F (40°C) Inlet Air Temperature	7.7	Add Heat if Humidity > 70%	14.0	Add Heat if Humidity > 70%	15.0
BIN B	86°F (30°C) Inlet Air Temperature	9.7	Add 18°F (10°C) Above Ambient Temperature	13.5	Add 18°F (10°C) Above Ambient Temperature	11.2
BIN C	Standard Bin (Normal Weather)	18.3	Standard Bin (Humid Weather)	34.7*	Standard Bin (Cold Weather)	33.5**

* Consists of 24.2 test days to dry to 15.8% plus 10.5 calculated days to complete drying later in the fall.

** Consists of 18.9 test days to dry to 16.0% plus 14.6 calculated days to complete drying in the spring.

Although the trends are similar to average drying results, the drying time increased considerably in all runs. Also, the advantages of drying with high inlet air temperatures were not as extreme. For example in Run 1, the drying time for Bin A was 22% of the standard bin "average drying" time, but was 42% of the standard bin "through drying" time. Similar trends occurred in the other two runs.

6.3 ENERGY CONSUMPTION

Propane, electrical, and total energy consumptions for average drying are shown in TABLE 7.

TABLE 7. Energy Consumption for Average Drying.

RUN	BIN	ENERGY FOR 1710 bu (46.5 t)						ENERGY PER UNIT GRAIN DRIED		SPECIFIC ENERGY CONSUMPTION	
		ELECTRICAL		PROPANE		TOTAL					
		MBtu	(GJ)	MBtu	(GJ)	MBtu	(GJ)	Btu/bu	(MJ/t)	Btu/lb	(kJ/kg)
1 (Aug.)	A 104°F (40°C) Inlet Air Temperature	0.69	(0.73)	9.36	(9.88)	10.0	(10.6)	5850	(224)	2680	(6230)
	B 86°F (30°C) Inlet Air Temperature	1.41	(1.49)	6.98	(7.28)	8.3	(8.8)	4850	(189)	2230	(5190)
	C Standard Bin (Normal Weather)	3.01	(3.18)	—	—	3.0	(3.2)	1750	(69)	800	(1860)
2 (Sept.)	A Add Heat if Humidity > 70%	2.44	(2.57)	7.73	(8.16)	10.1	(10.7)	5910	(230)	2710	(6300)
	B Add 18°F (10°C) Above Ambient Temperature	2.48	(2.62)	12.22	(12.89)	14.7	(15.5)	8600	(333)	3940	(9160)
	C Standard Bin (Humid Weather)	7.25	(7.65)	—	—	7.3	(7.7)	4270	(166)	1960	(4560)
3 (Oct.)	A Add Heat if Humidity > 70%	2.55	(2.69)	6.60	(6.96)	9.2	(9.7)	5380	(209)	2470	(5750)
	B Add 18°F (10°C) Above Ambient Temperature	2.13	(2.25)	11.25	(11.87)	13.4	(14.1)	7840	(303)	3590	(8350)
	C Standard Bin (Cold Weather)	6.83	(7.21)	—	—	6.8	(7.2)	3980	(155)	1820	(4230)

The standard bin (Bin C) used more electrical energy than the

other two bins in all cases. This was due to the drying time being longer for the standard bin.

In all cases where heat was added, propane energy consumption was much more than electrical consumption. This was expected. Natural air drying has always been regarded as a more efficient method of drying than any drying system that burns propane.

Because propane energy consumption was considerably higher than electrical energy consumption, total energy consumption for all "adding heat" runs was much higher than the respective standard bin. Total energy consumption for heated air tests ranged from 180 to 330% of the respective standard bin total energy consumption, even though drying times for the heated air tests were less.

The Run 1 results indicated that adding a large amount of heat to natural air drying resulted in a considerable increase in energy consumption, even though drying time was reduced considerably. Also, comparing total energy consumption of Bin A and B, it appeared that increasing the added heat resulted in more energy consumption.

Runs 2 and 3 used similar drying strategies, but were done at different times of the year. In both cases, the heater that was controlled by a humidistat (Bin A) used a similar amount of electrical energy, but 31% less propane energy than the continuously operating heater (Bin B). From these results, and the drying times discussed earlier, it appears that using a humidistat in adverse weather can save propane energy but results in similar drying times, compared to operating a heater without any controls.

Propane, electrical, and total energy consumptions for "through drying" are given in TABLE 8.

TABLE 8. Energy Consumption for "Through Drying".

RUN	BIN	ENERGY FOR 1710 bu (46.5 t)						ENERGY PER UNIT GRAIN DRIED		SPECIFIC ENERGY CONSUMPTION	
		ELECTRICAL		PROPANE		TOTAL					
		MBtu	(GJ)	MBtu	(GJ)	MBtu	(GJ)	Btu/bu	(MJ/t)	Btu/lb	(kJ/kg)
1 (Aug.)	A 104°F (40°C) Inlet Air Temperature	1.78	(1.88)	20.2	(21.3)	22.0	(23.2)	12900	(498)	1820	(4230)
	B 86°F (30°C) Inlet Air Temperature	2.18	(2.30)	10.8	(11.4)	13.0	(13.7)	7600	(294)	1540	(3580)
	C Standard Bin (Normal Weather)	4.00	(4.22)	—	—	4.0	(4.2)	2340	(90)	700	(1630)
2 (Sept.)	A Add Heat if Humidity > 70%	3.58	(3.78)	10.6	(11.2)	14.2	(15.0)	8300	(323)	2820	(6560)
	B Add 18°F (10°C) Above Ambient Temperature	3.32	(3.50)	16.4	(17.3)	19.7	(20.8)	11500	(447)	3460	(8050)
	C Standard Bin (Humid Weather)	8.23	(8.68)	—	—	8.2	(8.7)	4800	(187)	1430	(3330)
3 (Oct.)	A Add Heat if Humidity > 70%	3.60	(3.80)	10.6	(11.2)	14.2	(15.0)	8300	(323)	3280	(7630)
	B Add 18°F (10°C) Above Ambient Temperature	2.65	(2.79)	14.8	(14.8)	16.7	(17.6)	9770	(378)	3040	(7070)
	C Standard Bin (Cold Weather)	7.78	(8.22)	—	—	7.8	(8.2)	4560	(176)	1360	(3160)

The trends were similar to the "average drying" energy consumption results, but were higher in all cases. Also, the energy disadvantages to adding heat were much more pronounced. For example, in Run 1, total energy for the Bin A was 333% of the standard bin "average dry" total energy consumption, but was 550% of the standard bin "through dry" total energy consumption.

6.4 QUALITY OF WORK

6.4.1 Overdrying: Overdrying refers to drying grain below what is considered "dry" by the Canadian Grain Commission. For wheat, "dry" is 14.5%. Overdrying commonly occurs during natural

air drying in most parts of Saskatchewan due to low ambient relative humidity during the normal drying season. Because adding supplemental heat reduces the relative humidity of the drying air below ambient, it was expected that overdrying would be increased.

Grain moisture contents (m.c.) for all bins in Run 1, at "average dry", are given in TABLE 9.

TABLE 9. Run 1 (August) - "Average Dry" Layer Moisture Contents.

HEIGHT ABOVE FLOOR ft (m)	BIN A 104°F (40°C) Inlet Air Temperature	BIN B 86°F (30°C) Inlet Air Temperature	BIN C Standard Bin (Normal Weather)
16 (4.9)	17.2	17.9	17.5
13 (4.0)	17.3	17.3	15.7
10 (3.0)	17.6	17.4	15.2
7 (2.1)	18.1	14.6	13.2
4 (1.2)	10.1	11.4	12.5
1 (0.3)	6.8	10.3	11.6

High inlet air temperatures resulted in more overdrying at the bottom of the bin compared to natural air drying (6.8% m.c. in Bin A vs 11.6% m.c. in Bin C). This was not a major problem if the grain in the bin was mixed thoroughly immediately after the fan is shut off. However, if the grain was not mixed soon after the fan was shut off, the grain in Bins A and B (heat added) was more prone to spoilage than the standard bin, because more of the grain in the bin was at a high moisture content. Therefore, adding large amounts of heat made prompt grain mixing more necessary than normal natural air drying.

Grain m.c.'s for all bins in Run 1 after "through drying" are given in TABLE 10.

TABLE 10. Run 1 (August) - "Through Dry" Layer Moisture Contents.

HEIGHT ABOVE FLOOR ft (m)	BIN A 104°F (40°C) Inlet Air Temperature	BIN B 86°F (30°C) Inlet Air Temperature	BIN C Standard Bin (Normal Weather)
16 (4.9)	12.7	14.8	14.4
13 (4.0)	7.6	10.4	12.7
10 (3.0)	7.3	11.1	12.8
7 (2.1)	6.7	10.4	12.5
4 (1.2)	6.2	9.9	12.6
1 (0.3)	5.7	9.3	13.1
AVERAGE	6.9	10.4	12.8

"Through drying" with large amounts of heat was undesirable, as it resulted in drastic overdrying. This represented a large hidden cost, as the extra water removed from the grain reduced the total saleable weight.

Grain m.c.'s for both bins with heaters (Bins A and B) in Run 2 after "through drying" are given in TABLE 11.

TABLE 11. Run 2 (September) - "Through Dry" Layer Moisture Contents.

HEIGHT ABOVE FLOOR ft (m)	BIN A Add Heat if Humidity > 70%	BIN B Add 18°F (10°C) Above Ambient Temperature
16 (4.9)	14.8	14.6
13 (4.0)	13.5	12.9
10 (3.0)	13.3	13.5
7 (2.1)	13.3	12.9
4 (1.2)	13.2	12.7
1 (0.3)	13.2	12.0
AVERAGE	13.4	12.9

Using a humidistat to control the heater resulted in less overdrying and more uniform moisture contents in the bin once drying

was completed. This reduced overdrying costs, and promoted safer storage once drying was completed. Even though heat was added in Run 2, overdrying was less than or nearly equal to normal natural air drying (Run 1, Bin C). Thus, when used in small amounts, and in the correct weather conditions, adding heat could be used to dry grain without abnormal overdrying.

Results from Run 3 showed similar trends to those in Run 2.

6.4.2 Grain Quality: In this project, grain quality was analyzed by three methods: grade tests, baking quality, and germination. Grade was the most important factor since the grade determines the grain price. Grade was determined by visual examination of the grain. Baking quality tests measured the ability of wheat to form a loaf of bread. These tests are not conducted at elevators, since baking quality cannot be determined visually. Therefore, it is possible for wheat to be graded high even though the baking quality may be poor. Germination is not measured in determining the quality of milling wheat. However, germination tests were conducted in this project since germination is normally reduced similarly to baking quality, and thus provides a good quantitative verification of baking quality results.

Grain quality results are given in TABLE 12.

TABLE 12. Grain Quality Results.

	RUN 1 (August)	RUN 2 (September)	RUN 3 (October)
BIN A	104°F (40°C) Inlet Air Temperature	Add Heat if Humidity 70%	Add Heat if Humidity 70%
Grade Loss	none	none	none
Baking Quality	not damaged	not damaged	not damaged
Germination Drop, %	0	1	6
BIN B	86°F (30°C) Inlet Air Temperature	Add 18°F (10°C) Above Ambient Temperature	Add 18°F (10°C) Above Ambient Temperature
Grade Loss	none	none	none
Baking Quality	not damaged	not damaged	not damaged
Germination Drop, %	0	2	6
BIN C	Standard Bin (Normal Weather)	Standard Bin (Humid Weather)	Standard Bin (Cold Weather)
Grade Loss	none	none	none
Baking Quality	not damaged	not damaged	not damaged
Germination Drop, %	0	3	1*

*These were measured at the end of tests in the fall and were not projected to the spring.

No grade reduction occurred in these tests. This was expected. None of the drying treatments were very harsh as the drying air temperatures were all below recommended safe temperatures.

None of the grain used in these tests had its baking quality damaged. This was expected, as drying air temperatures were below the recommended safe temperatures for baking quality.

There was no serious reduction in germination for any of the grain drying treatments used in these tests. Because none of the drying treatments were very harsh, no germination reduction was expected. It's possible that a greater germination drop could have occurred if Run 3 on Bin C had continued through the winter. In another project at PAMI, wet grain stored through the winter had a

considerable germination drop. This is especially critical for seed farmers. However, no further tests were done in this project, since the wheat was milling wheat and germination does not affect grade.

6.4.3 Condensation: Condensation on the underside of the bin roof can occur during drying if warm, humid air contacts a cold roof. This is undesirable, as the water drips down onto the grain. This causes a reduction in drying rate. More seriously, it may promote spoilage due to very high moisture grain at the top of the bin.

Condensation occurred in Bin A during Run 1. Besides reducing the drying rate, this condensation also resulted in some minor grain spoilage at the top of the bin. If this same drying strategy was used in cooler ambient temperatures, condensation would probably be increased.

6.5 EASE OF OPERATION AND ADJUSTMENT

6.5.1 Manpower Requirements: In general, natural air drying had low labour requirements. The operator had to only fill the bin, turn on the fan, monitor the drying process, and possibly mix the grain after drying was completed. Both normal natural air drying and adding supplemental heat resulted in the same low labour input. Because the process occurred faster during supplemental heat drying, sampling occurred more frequently that natural air drying over a shorter period of time.

Adding a large amount of supplemental heat resulted in increased management requirements. When more heat was added, the process was occurring faster, and more frequent monitoring was required. Also, when the bin was "average dry", there was a larger

moisture gradient when more supplemental heat was added, compared to natural air drying or adding a small amount of heat. This required the operator to mix the grain soon after drying was completed to ensure that the wet grain at the top of the bin did not spoil.

Humidistats, thermostats, or other control devices reduced the labour requirements by controlling the burner automatically.

When adding heat, the operator periodically had to check the propane supply to ensure that the heater did not run out of fuel. This added labour would be eliminated if natural gas was used as a heater fuel.

If high drying air temperatures are used, operators should cool the grain after drying is completed. This promotes safe grain storage.

6.5.2 Installation: Installing the heaters required slightly more time than installing the fan alone. Persons installing the heater had to ensure that the fuel lines and electrical hookups were done according to applicable safety standards. Only CSA or CGA approved heaters should be used. Before startup, the operator had to familiarize himself with operation of the heater. Heaters and their controls may also require startup maintenance for proper operation.

6.5.3 Adjustment: Since a humidistat or thermostat was used to control the heater, these had to be set when the system was started up. Periodically, the units had to be checked to ensure that they were operating properly. The scale on the humidistat or thermostat was checked for correct calibration to ensure that the desired control affect was obtained.

6.5.4 Servicing: No servicing was required during these tests. However, because the heater has some moving parts and associated controls, service requirements would be slightly higher than a fan alone.

7. SIMULATION MODEL DEVELOPMENT

7.1 DRYING TIME

7.1.1 Model Assembly: In a drying process, four simultaneous operations may be present: heating, cooling, drying, and rewetting. A natural air drying simulation must account for all of these operations and also adjust for changing ambient conditions.

The model used in the simulation for this project has been derived from a deep bed drying model based on heat and mass transfer on a thin layer of grain, proposed by Thompson et al (1968), as detailed in APPENDIX VII. Using this model, a drying temperature based on the sensible heat balance between the air and grain was calculated. The equilibrium moisture content and drying rate of the grain were then estimated using this temperature. Changing ambient conditions were constantly updated in this simulation.

Temperatures and relative humidities during natural air drying in the Canadian prairies fluctuate between 23 to 95°F (-5 to 35°C), and 30 to 100%, respectively. At present, continuous and reliable data on mositure desorption and absorption rates, equilibrium moisture contents, and physical properties of most prairie grown grains are not known. In this work, the existing limited data has been extrapolated, so the results required verification.

7.1.2 **Model Verification:** The simulated moisture contents were compared to the experimental drying data collected during field tests. Acutal hourly dry bulb temperatures and humidities collected during the field tests were used as inputs to the drying simulation program. The experimental and simulated moisture contents for all nine runs are given in TABLE 13.

TABLE 13. Comparison of Experimental and Simulated Moisture Contents.

RUN	BIN	TIME TO "AVERAGE DRY" days		DIFFERENCE %
		Exp.	Sim.	
1 (Aug.)	A 104°F (40°C) Inlet Air Temperature	2.5	2.4	4
	B 86°F (30°C) Inlet Air Temperature	6.5	4.9	-24
	C Standard Bin (Normal Weather)	12.6	9.5	-24
2 (Sept.)	A Add Heat if Humidity > 70%	7.9	9.75	23
	B Add 18°F (10°C) Above Ambient Temperature	8.8	5.7	-35
	C Standard Bin (Humid Weather)	*	*	*
3 (Oct.)	A Add Heat if Humidity > 70%	9.4	6.5	-30
	B Add 18°F (10°C) Above Ambient Temperature	7.2	2.9	-60
	C Standard Bin (Cold Weather)	*	*	*
OVERALL AVERAGE DIFFERENCE				-21%

* These runs did not reach "average dry" in the test.

Overall, the simulated run reached "average dry" about 21% faster than the experimental runs. The difference was acceptable for this project, since they were relatively constant and reflect

the real trends, regardless of drying strategy. In the future, the reason for this difference should be investigated to determine whether program modifications are necessary. More detailed experimental vs simulation comparisons comparing moisture contents are given in APPENDIX VIII.

7.2 ENERGY CONSUMPTION

7.2.1 Model Assembly: Energy consumption was calculated from the previously determined drying time multiplied by the amount of energy consumed by the system per unit time. For natural air drying without heat, energy consumption consisted of the electrical energy needed to run the fan. This was calculated from the airflow rate and the computed pressure drop through the grain. The power requirement was then factored up by a typical fan efficiency to obtain the power consumed per unit time.

Energy consumption while adding supplemental heat was the sum of the electrical energy mentioned above and the energy used to heat the air as it passed into the bin. The added heat energy was calculated based on the airflow, specific heat, and temperature differences of the airstream as it passed over the heater.

7.2.2 Model Verification: The simulated electrical and fuel energy consumption was compared to the experimental data using the same inputs as the drying rate verification. The experimental and simulated energy consumption are given in TABLE 14.

TABLE 14. Comparison of Experimental and Simulated Energy Consumption.

RUN	BIN	ELECTRICAL ENERGY CONSUMPTION		PROPANE ENERGY CONSUMPTION		TOTAL ENERGY CONSUMPTION		DIFFERENCE
		Experimental MBtu (GJ)	Simulated MBtu (GJ)	Experimental MBtu (GJ)	Simulated MBtu (GJ)	Experimental MBtu (GJ)	Simulated MBtu (GJ)	%
1 (Aug.)	A 104°F (40°C) Inlet Air Temperature	0.69 (0.73)	2.74 (2.89)	9.36 (9.88)	6.72 (7.09)	10.1 (10.7)	9.5 (10.0)	-6
	B 86°F (30°C) Inlet Air Temperature	1.41 (1.49)	6.17 (6.51)	6.98 (7.36)	7.62 (8.04)	8.3 (8.8)	13.8 (14.6)	66
2 (Sept.)	A Add Heat if Humidity > 70%	2.44 (2.57)	7.68 (8.10)	7.73 (8.16)	7.36 (7.76)	10.2 (10.7)	15.0 (15.9)	47
	B Add 18°F (10°C) Above Ambient Temperature	2.48 (2.62)	9.24 (9.75)	12.22 (12.89)	10.36 (10.93)	14.7 (15.5)	19.6 (20.7)	33
3 (Oct.)	A Add Heat if Humidity > 70%	2.55 (2.69)	9.70 (10.23)	6.60 (6.96)	6.56 (6.92)	9.2 (9.7)	16.2 (17.2)	77
	B Add 18°F (10°C) Above Ambient Temperature	2.13 (2.25)	9.26 (9.77)	11.25 (11.87)	14.60 (15.40)	13.4 (14.1)	23.9 (25.2)	78
						OVERALL AVERAGE DIFFERENCE		49%

The experimental electrical energy consumption data did not closely agree with the simulated results. Simulated results were about three times higher than the corresponding experimental results. This difference was caused by the calculated pressure drop in the simulation being much higher than the pressure drop recorded during field tests. This calculated pressure drop was derived from theory, and therefore may not have applied to the specific grain used in these tests. Since the electrical energy consumption calculated in the simulation was based on the calculated pressure drop, all electrical energy consumption values were relatively high. However, pressure drops and electrical energy consumptions calculated in the following "Results" section appeared to be reasonable. Since the drying rate results were acceptable, results should be accurate.

Experimental propane consumption values agreed very well with the simulated values. Most experimental values agreed within 10% of the simulated values.

Simulated total energy was about 50% higher than the experimental values. This is due to the abnormally high electrical energy simulated results. However, the values obtained in the "Results" section appear to be realistic, so the simulation appeared acceptable. In the future, the reason for this difference should be investigated to determine whether program modifications are necessary.

7.3 GRAIN QUALITY

7.3.1 Model Assembly: The time in days, d, before germination of stored grain drops by 5 percent has been related to the storability of grain by the following equation, (Frazer and Muir, 1981):

$$\text{Log}(d) = 6.234 - 0.2118M - 0.053T \qquad [1]$$

for $12\% \leq M \leq 19\%$, and

$$\text{Log}(d) = 4.129 - -0.010M - 0.058T \qquad [2]$$

for $19\% \leq M \leq 24\%$.

During each time step Δt an allowable storage time, t_m, is estimated using either [1] or [2]. The accumulated ratio $\Delta t/t_m$ called the storage time index (STI) over the drying period is an indication of the state of the grain quality. As the STI value approaches unity, the stored grain deteriorates further towards the loss of 5 percent germination.

Overdrying: Overdrying, although not a visible quality loss, can be a significant loss in the weight of grain at the time of

sale. Number One Canadian wheat is sold on a weight basis at 14.5 percent moisture content. The water lost in overdrying below this moisture content represents a direct loss in grain weight. Overdrying as a percent of total grain weight is calculated by the following equation:

$$E_w = 85.5 \left(\frac{14.5}{85.5} - \frac{M_f}{100-M_f} \right) \qquad [3]$$

Where M_f is the average final moisture content, in percent wet basis.

7.3.2 **Model Verification:** The storage index analysis used in the computer simulation bases all quality decreases on germination alone. Because more factors, such as heat damage and spoilage, are involved in determining the final grain quality, this model was not used in further analysis.

It would be useful to have the quality simulations improved to include other prairie storage problems, such as heat damage and spoilage.

7.4 COST MODELS

7.4.1 **Model Assembly:** The drying cost, C, in ¢/bu ($/t) is calculated by the following sum:

$$C = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8 \qquad [4]$$

where C_1 to C_8 are the fixed and variable costs described in the following sections.

Fixed and variable costs were determined for each bin dried. Costs were based on the amount of moisture removed and the length of time required to complete drying.

Capital Cost: The ratio, F_r, of the average annual capital cost to the initial cost of the dryer can be expressed as follows (Audseley and Boyce, 1974):

$$F_r = i\left(\frac{1+r}{2} + \frac{1-r}{2n}\right) + \frac{1-r}{n} \qquad [5]$$

where i is the interest rate, r is the ratio of resale value, and n is the life of the equipment. For the perforated floor, the life was assumed to be 20 years. The life of the heater, fan, and controller was calculated using:

$$n = 10 * \frac{504}{L} \qquad [6]$$

where L is the number of hours used per year.

The fixed purchase cost C_1, is estimated by:

$$C_1 = C_o F_r \qquad [7]$$

where C_o is the initital purchase cost of the dryer.

Repair Cost: The fixed repair cost, C_2, is estimated as follows:

$$C_2 = C_o R_c \qquad [8]$$

Where R_c is a ratio of the repair cost to the initial cost of the dryer.

Labour Cost: The labour cost, C_3, consisted of the costs associated with filling the bin and monitoring the drying process, along with any mixing costs that were necessary if the bin of grain was "average dried". Monitoring costs were considered equal for all types of drying, as the same amount of labour input was required regardless of the drying time. Mixing costs were included if the bin was "average dried", and not included if the bin was "through dried".

Energy Cost: The energy cost, C_4, consisted of both electrical energy and fuel energy cost. The total energy cost was calculated as follows:

$$C_4 = (EC)(E_c) + (FC)(F_c) \quad [9]$$

where EC is the electrical energy consumption and E_c is the cost of electricity per unit of energy. Both propane and natural gas fuels were investigated, with FC being the amount of fuel energy used, and F_c being the cost of fuel per unit of energy. The heat content of various energy sources and the method of calculating the basic energy prices are summarized in APPENDIX VII.

Inventory Cost: The inventory cost, C_5, was taken to be the cost of having the grain stored in the bin, unsold, due to it not being dry. This cost would be derived from the lost interest on the selling price of the grain during the time that it is unsold. Using W as the grain height, and P_1 as the price of 1 CWRS wheat per unit weight, the inventory cost can be estimated by:

$$C_5 = \frac{W\ P_1\ i\ h}{8760} \quad [10]$$

where i is the interest rate and h is the number of hours that the grain remained in the bin.

Deterioration Cost: If the grain temperature and moisture content remain high for an extended period of time, there is a risk of spoilage. It is assumed that when the storage time index reaches a value of 1, the grain has downgraded from 1 CWRS to feed:

$$C_6 = (P_1 - P_f)(W)(STI) \quad [11]$$

where P_f is the price of feed wheat per unit weight and STI is the storage time index calculated in the computer simulation.

Overdrying Cost: When the average moisture content of the grain in the bin reaches 14.5%, grain at the bottom of the bin may be overdry, while grain at the top of the bin may still be at the initial moisture content. If drying continues until the grain at the top of the bin is at 14.5%, the rest of the grain in the bin will be overdried. Overdrying results in a loss of grain weight that is available for sale.

$$C_7 = W_o P_1 \qquad [12]$$

where W_o is the weight of the water lost in overdrying.

Late Harvest Cost: If the grain is left in the field unharvested, there is a risk of the grain being downgraded due to rain or frost damage. The associated risk cost, C_8, can be estimated by:

$$C_8 = \left(\frac{M_i - M_h}{M_i - 14.5}\right)(W)(P_1 - P_f)(p) \qquad [13]$$

where M_i = initial moisture content at which, if the grain is harvested, there would be no risk, M_i = 22%.

M_h = harvest moisture content.

p = probability of bad weather

p = 0.20 if harvest date is August 1

p = 0.25 if harvest date is September 1

p = 0.33 if harvest date is October 1

The above probabilities are estimates, based on field experience.

7.4.2 Model Verification: Since most elements of the cost model used well established principles, no verification was conducted for these elements other than manual random calculation to ensure the

equations had been entered and applied correctly. The probabilities used in the late harvest cost (C_8) could not be verified as sufficient field data, required to assign realistic values, was not available.

8. SIMULATION RESULTS

8.1 SCOPE OF SIMULATIONS

8.1.1 Drying Time and Energy Consumption: Several supplemental heat control strategies were simulated and compared. Investigated control strategies included: (1) using a thermostat to control the heater and hold inlet air temperatures at 50, 68, and 104°F (10, 20, and 40°C), (2) using a humidistat to control the heater so humidity did not exceed 70%, (3) letting the heater run constantly using no control to add just enough heat so air temperature was heated by 9 and 18°F (5 and 10°C), (4) natural air drying with no supplemental heat added.

All drying was simulated on a bin 14 ft (4.3 m) in diameter and 14 ft (4.3 m) in height with a holding capacity of about 1740 bu (47 t) of wheat (at 14.5% moisture content). The bin had a fully perforated floor and a natural air drying fan.

Initial moisture contents of 16, 19, and 22% were used. The grain was dried to a final moisture content of 14.5% when "average drying". When "through drying", the system was operated until the top layer of the bin reached 14.5%. Airflow rates were 0.5, 1.0, 1.5, and 2.0 cfm/bu (6.5, 13, 19.5, and 26 $L/s.m^3$).

Input air conditions were extracted from a weather data file representing the typical climate of Saskatoon. This file contained

hourly temperatures and relative humidities. Start dates of August 1, September 1, and October 1 were used to simulate drying in early fall, normal harvest weather, and late fall conditions. When drying was not completed by November 1, the fan was shut off and drying reinstated on May 1. Detailed assumptions and tables of results are given in APPENDIX VIII.

8.1.2 Economic Analysis: The following assumptions were made:

1. Equipment Value.
   - drying floor costs $700.
   - fan cost = ($1,000) $(cfm/bu)^{0.6}$
     = [$1,000 $(L/s.m^3/13)^{0.6}$].
   - heater costs $1,200.
   - heater control (humidistat or thermostat) costs $175.
2. Service Life.
   - drying floor and ducts = 20 years.
   - fan, heater, and controller = 5,040 hours.
3. Energy costs.
   - electricity = 4.5¢/kWh.
   - propane = $1.20/gal (26.4¢/L).
   - natural gas = 0.37¢/ft^3 (12.89¢/m^3).
4. Rates.
   - resale value = 10% of purchase cost.
   - interest rate = 7% per annum.
   - repair and insurance = 1% per annum.
5. Wheat prices.
   - 1 CWRS = $3.45/bu ($127/t).
   - Canada feed = $2.44/bu ($90/t).

The cost of the drying bin was not included in this analysis, as this was considered to be associated to grain storage. To keep costs comparable with other drying systems not dealt with in this study, non-direct costs, such as inventory, deterioration, and late harvest costs have not been included in this section.

8.2 DRYING TIME

8.2.1 Effect of Initial Moisture Content: Total times to "average dry" as affected by initial moisture content for five drying strategies are shown in FIGURE 2.

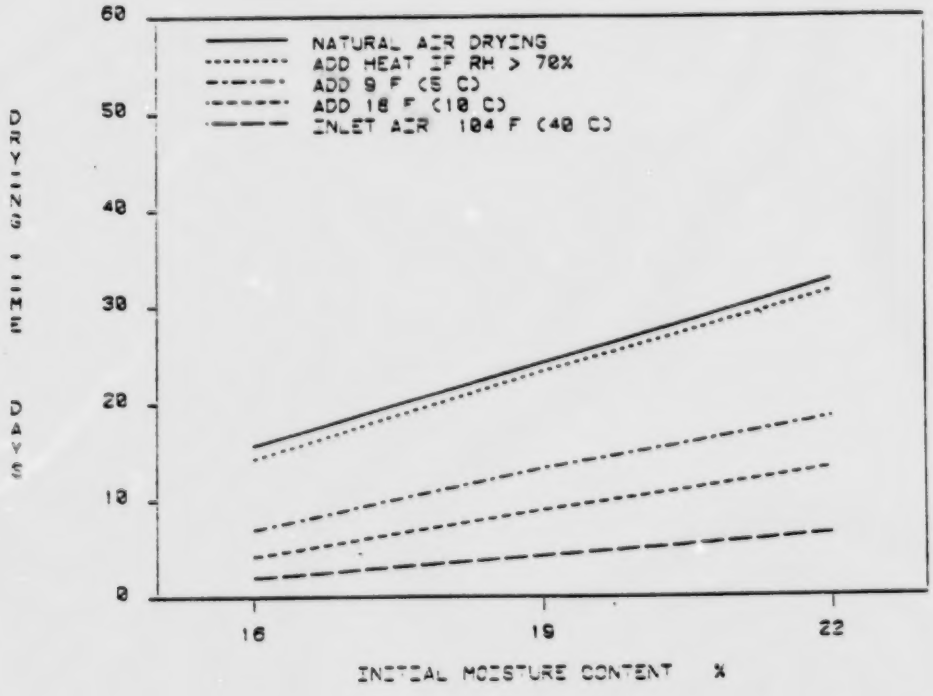

FIGURE 2. Effect of Initial Moisture Content on Time to "Average Dry". [Start Date: Sept. 1, Airflow Rate: 1 cfm/bu (13 L/s.m^3)].

As initial moisture content increased, drying time increased for all strategies used. For example, when natural air drying, the drying

increased from 15.7 to 32.7 days as initial moisture content increased from 16 to 22%. This was expected. High initial moisture contents required more water to be removed so more drying time was required.

The drying times decreased as the amount of added heat was increased. Holding the inlet air temperature at 104°F (40°C) resulted in the quickest drying times. When drying from 19%, drying only took 4.3 days compared to 24.2 days for natural air drying. Continuously adding 18°F (10°C) resulted in the second lowest drying time of the 9.0 days. Controlling the humidity to keep it below 70% did not reduce the drying time much. Drying time was 23.3 days. This likely occurred because the humidities in the Saskatoon area do not rise above 70% very often during September. Therefore, the heater would seldom operate.

This slight increase in drying time was different than the field test results where controls set by humidity resulted in similar times to continuously adding heat. It should be noted that in this simulation only enough heat was added to keep the humidity at 70%. If the heater is set to add more heat when humidities exceed the set point, then logically more drying is expected. Also, unfavourable weather during field tests resulted in the humidistat controlled heater running for the majority of the time. Therefore, humidistat controlled and continuous heat strategies should have similar results in the high humidity field test conditions. In typical years, humidity control would have similar characteristics to the simulated results.

The effect of heat on drying times was expected because as more

heat is added, the drying system more closely approaches a high-speed hot air drying system. This indicates very high air temperatures should be used. However, in later sections, the disadvantages of excessively high temperatures will be discussed.

8.2.2 Effect of Start Date: Times to "average dry" as affected by start date are shown in FIGURE 3.

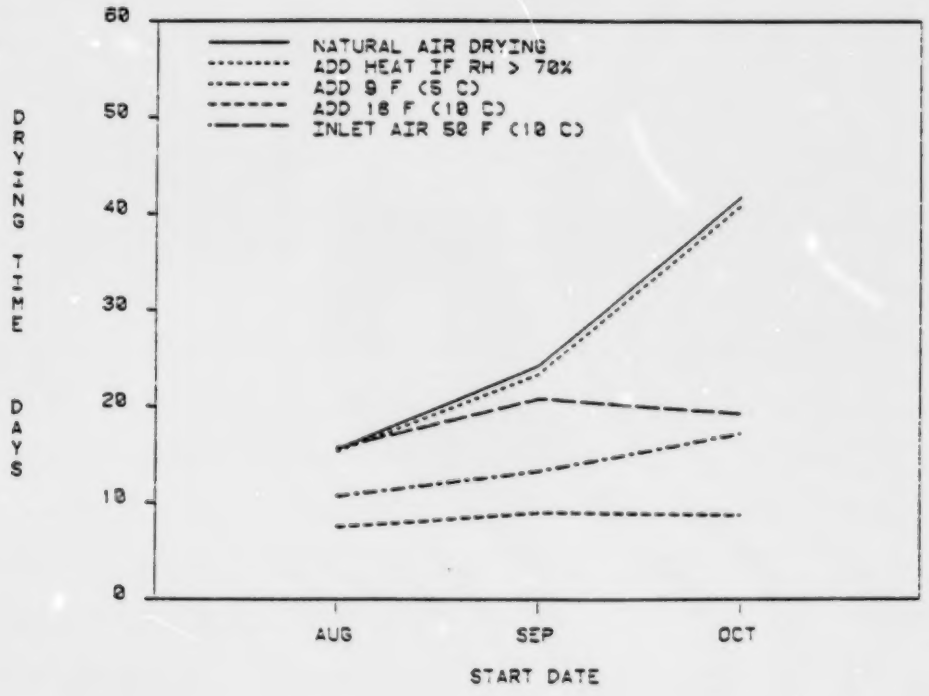

FIGURE 3. Effect of Start Date on Time to "Average Dry". [Initial Moisture Content: 19%, Airflow Rate: 1 cfm/bu (13 L/s.m^3)].

As the start date was delayed, drying time increased. This was attributed to the cooler, more humid weather decreasing the drying rate. In fact, natural air drying which started on October 1 was not completed in the fall. Using a humidistat to keep the humidity of the incoming air below 70% was similar to natural air drying. Drying time in August and September decreased by less than 1 day. In

October, drying was not completed. It appeared that the cool October weather prevented drying even if the humidity was lowered.

However, adding as little as 9°F (5°C) decreased drying time in August and September by about 40% to 10.7 and 13.3 days, respectively. In October, it allowed drying to be completed. Continuously adding 18°F (10°C) in October allowed drying to be completed in 8.7 days which was less time than any other strategy noted here.

In this instance, the drying time in October was slightly less than the drying time in September. This does not follow the trend exhibited by other drying runs. This could be because the weather data used for these simulations had a period of favourable drying weather at the beginning of October. Because this drying run in October lasted only 8.7 days, this good weather formed the majority of the run. Immediately after this run was completed, the weather data became unfavourable for natural air drying. This trend is not typical.

The more realistic trend is that delayed drying will increase drying time. Hence, operators should be encouraged to complete their drying early before bad weather sets in later on in the fall.

8.2.3 Effect of Airflow Rate:

August

The time to "average dry" as affected by airflow rate in August is shown in FIGURE 4.

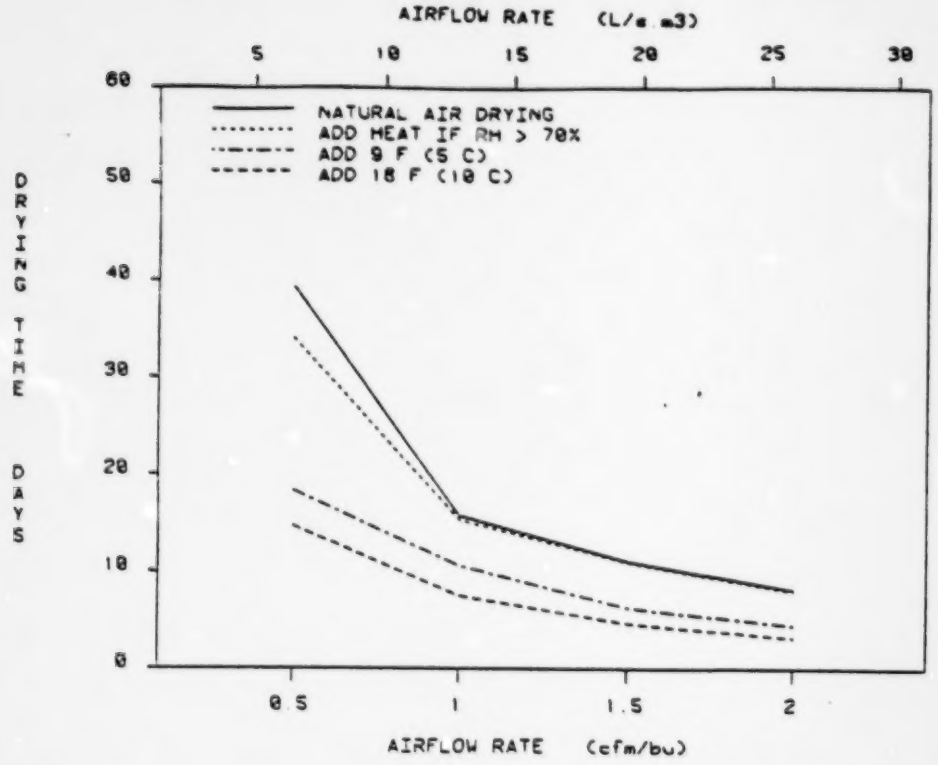

FIGURE 4. Effect of Airflow Rate on Time to "Average Dry" Starting August 1. [Initial Moisture Content: 19%].

As the airflow rate increased, drying time decreased. Generally, airflow rate and drying time were directly related. However, when natural air drying with 1 cfm/bu (13 L/s.m^3) compared to 0.5 cfm/bu (6.5 L/s.m^3), the drying time decreased by 60% from 39.3 to 15.7 days. This was more than the anticipated 50% decrease. It appeared that the higher airflow rates also captured the additional drying advantage of the early warm weather.

Adding heat, even in August, decreased drying time considerably. When adding 9°F (5°C) at 1 cfm/bu (13 L/s.m^3), drying time was decreased by 32% to 10.6 days. When adding 18°F (10°C), drying time was decreased by 52% to 7.5 days. However, controlling the humidity below 70% had little effect.

October

Total drying time as affected by airflow rate in October is shown in FIGURE 5.

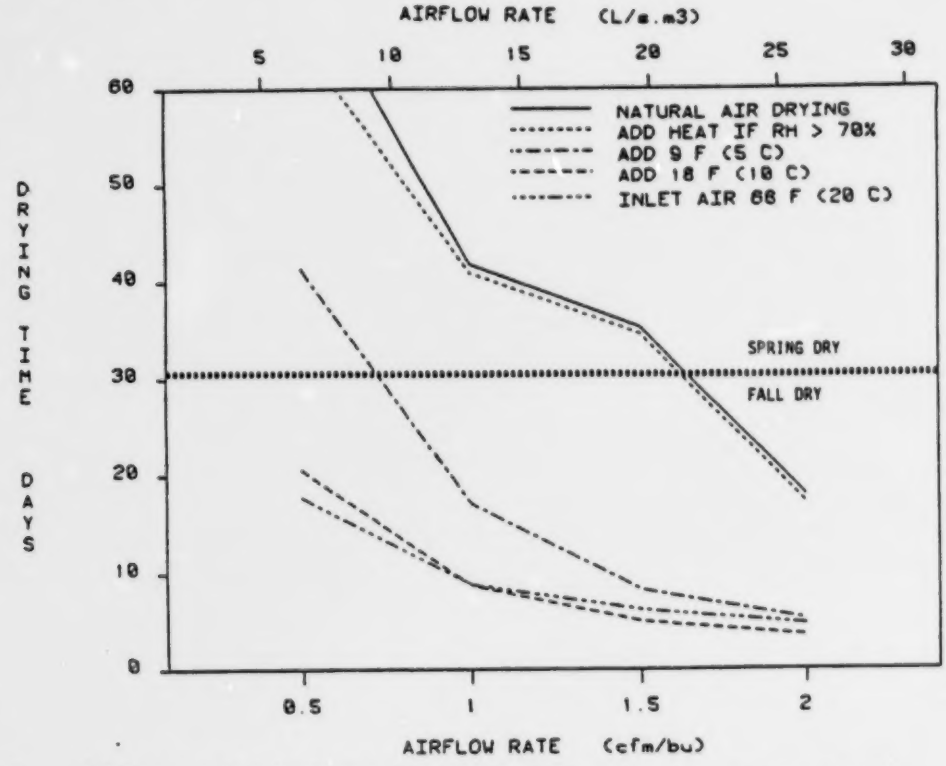

FIGURE 5. Effect of Airflow Rate on Time to "Average Dry" Starting October 1. [Initial Moisture Content: 19%].

Only 2 cfm/bu (26 L/s.m^3) allowed natural air or humidity controlled drying to be completed in the fall. When 9°F (5°C) was added continuously, at least 1 cfm/bu (13 L/s.m^3) was needed to complete drying in the fall. Adding 18°F (10°C) allowed drying to be completed in the fall, regardless of the airflow rate used.

8.2.4 Effect of "Average Drying" vs "Through Drying": The percent of increased drying time due to "through drying" compared to "average drying" the grain as affected by initial moisture content is given in FIGURE 6.

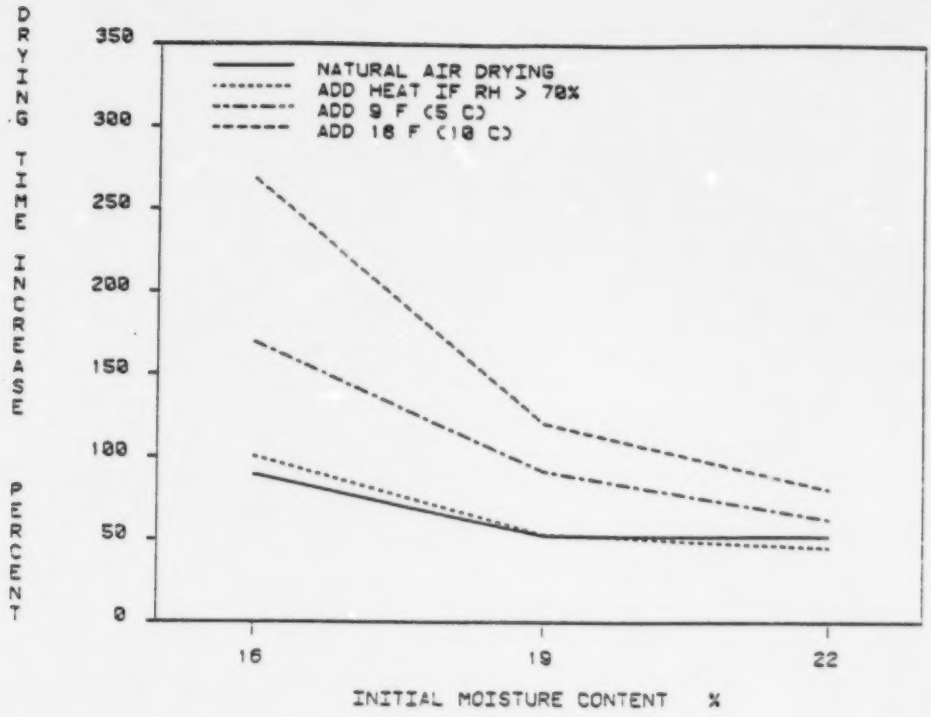

FIGURE 6. Effect of "Average" vs "Through Drying" on Drying Time. [Start Date: Sept. 1, Airflow Rate: 1 cfm/bu (13 L/s.m^3)].

In all cases, "through drying" resulted in a longer drying time than "average drying". The differences were much larger when heat was added. At 19% initial moisture content, the increase was only 52% when natural air drying, but it was 91 and 120%, respectively, when adding 9°F (5°C) and 18°F (10°C). Even larger drying time differences occurred at 16% initial moisture content. These relatively high drying time increases should encourage farmers to stop their fan and mix their grain once an "average dry" is achieved. "Through drying" eliminates mixing, but results in a much higher drying time.

8.3 ENERGY CONSUMPTION

8.3.1 Effect of Initial Moisture Content: Energy consumption as affected by initial moisture content is shown in FIGURE 7.

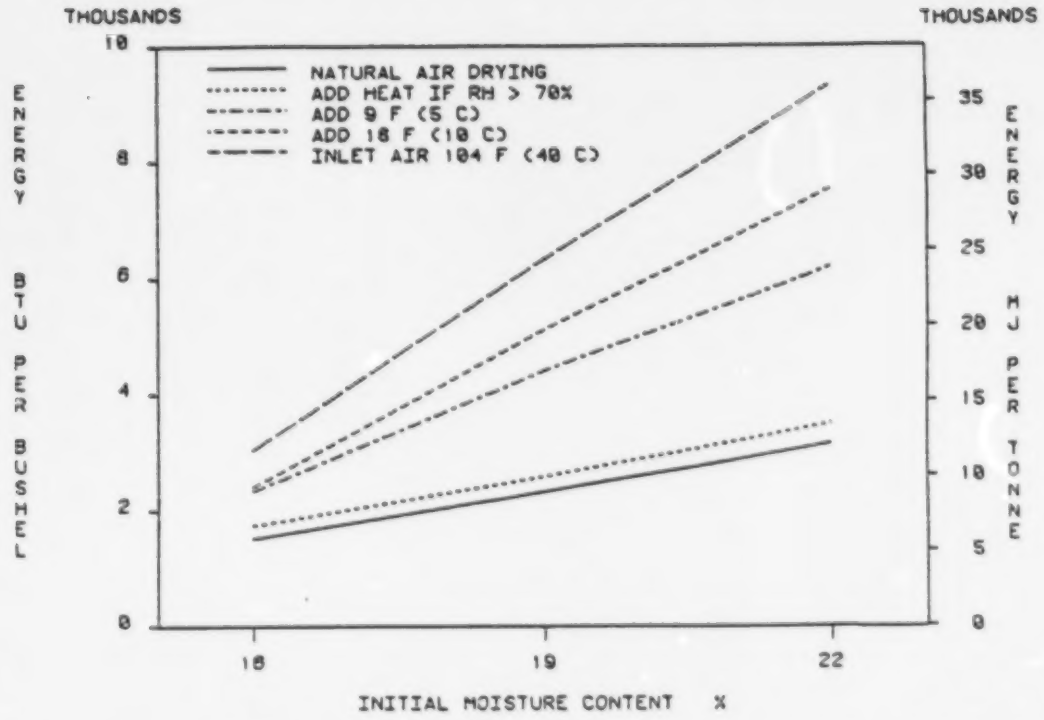

FIGURE 7. Effect of Initial Moisture Content on Energy Consumption. [Start Date: Sept. 1, Airflow Rate: 1 cfm/bu (13 L/s.m^3).]

As initial moisture content increased, energy consumption also increased for all drying strategies. This was as expected because as initial moisture content is increased, more water has to be removed to dry the grain, and thus more energy must be input into the system.

Also, as more heat was added, energy consumption increased. Natural air drying used the least amount of energy. At 19% initial moisture content, energy consumption was 2340 Btu/bu (91 MJ/t). Warming the inlet air to 104°F (40°C), increased energy consumption greatly to 6330 Btu/bu (245 MJ/t). This approached the typical hot air dryer efficiency of 7000 Btu/bu (271 MJ/t) reported by Lischynski (1986).

This should discourage operators from adding large amounts of heat through their natural air drying fan, as energy consumption will approach that of hot air drying, but the drying rate will be much less than hot air drying.

8.3.2 Effect of Start Date: Energy consumption as affected by the start date is shown in FIGURE 8.

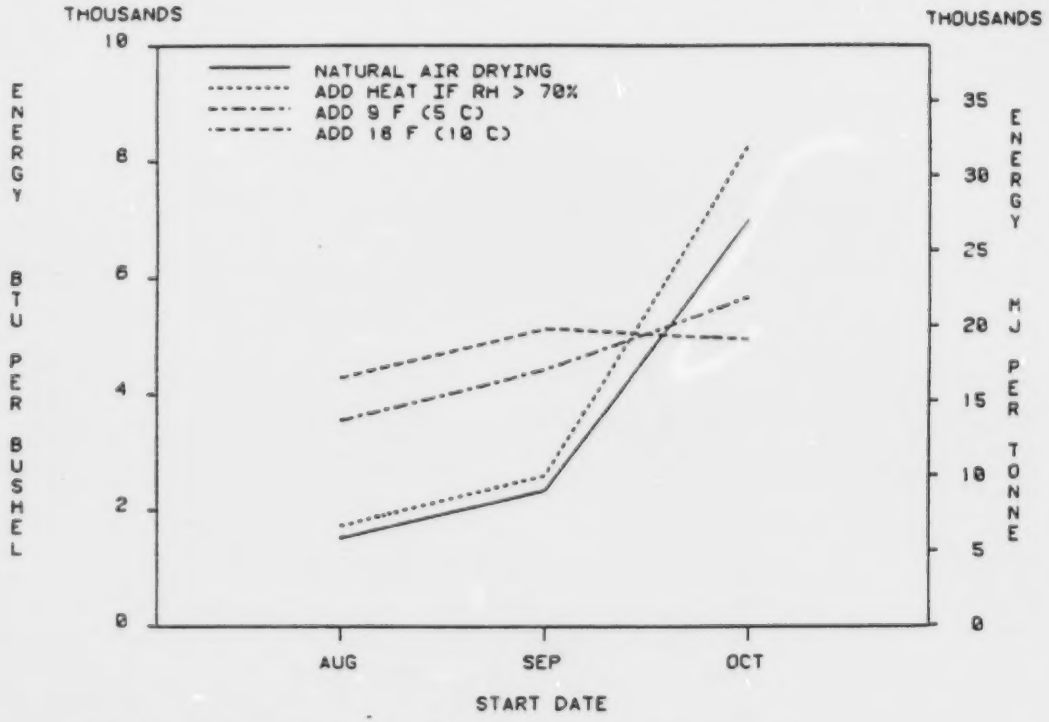

FIGURE 8. Effect of Start Date on Energy Consumption. [Initial Moisture Content: 19%, Airflow Rate: 1 cfm/bu (13 L/s.m^3)].

Energy consumption increased as the start date was delayed. In August and September, adding heat consumed about 100% more energy than natural air drying. However, when starting in October, energy consumption of natural air drying increased considerably and exceeded most adding heat strategies. This was because drying was not completed in the fall. It was noteworthy that natural air drying and controlling the humidity at 70% both consumed as much energy as a hot air dryer.

"Through drying" the grain, as opposed to "average drying" the grain and mixing, resulted in higher energy consumption. This was due to increased heat and electrical input to keep the fan and heater running for a longer period of time.

8.4 QUALITY OF WORK

8.4.1 Overdrying: Overdrying refers to drying grain below what is considered "dry" by the Canadian Grain Commission. For wheat, "dry" is 14.5%. Overdrying normally occurs when the bin of grain is "through dried". This is because when the bin is "through dried", the entire bin of grain is at a moisture content that is in equilibrium with the ambient air. Because the ambient air relative humidity in most parts of Saskatchewan results in an equilibrium moisture content below 14.5% during most of the drying season, overdrying can become a major problem if the grain is "through dried".

The effect of initial moisture content on overdrying when "through drying" in September is given in FIGURE 9.

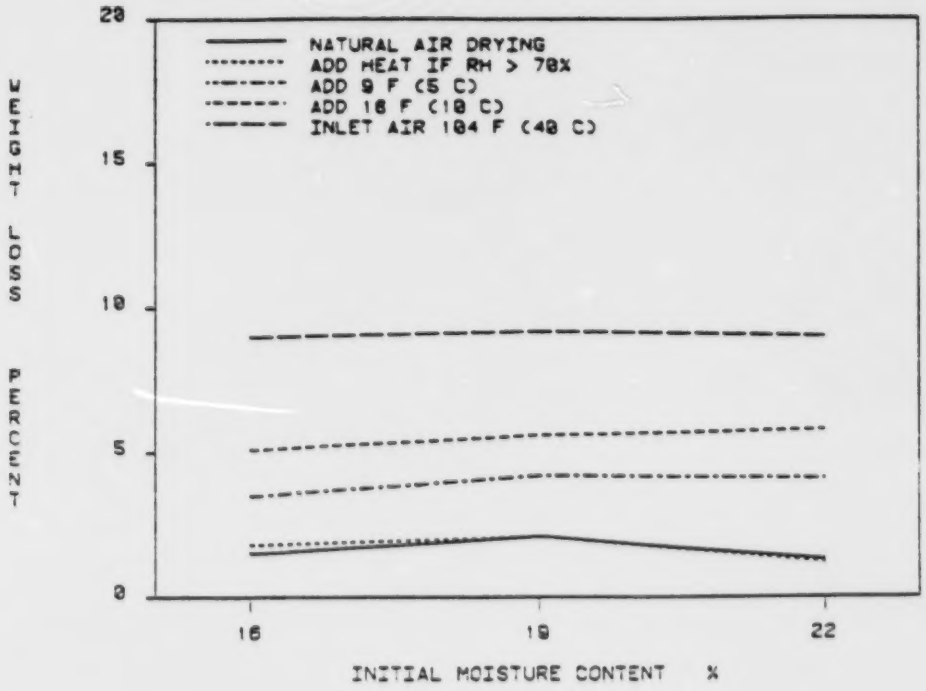

FIGURE 9. Effect of Initial Moisture Content on Overdrying when "Through Drying".
[Start Date: September 1, Airflow Rate: 1 cfm/bu (13 L/s.m^3).

As the initial moisture content increased, the amount of overdrying increased slightly. When adding 18°F (10°C) continuously, overdrying increased from 5.1 to 5.8% as the initial moisture content increased from 16 to 22%.

The most significant increase in overdrying resulted from adding heat. When natural air drying from 19%, overdrying was only 2.1%. As the amount of added heat was increased, the overdrying increased greatly. When heating to 104°F (40°C), overdrying was 9%!

The effect of the start date on overdrying when "through drying" is given in FIGURE 10.

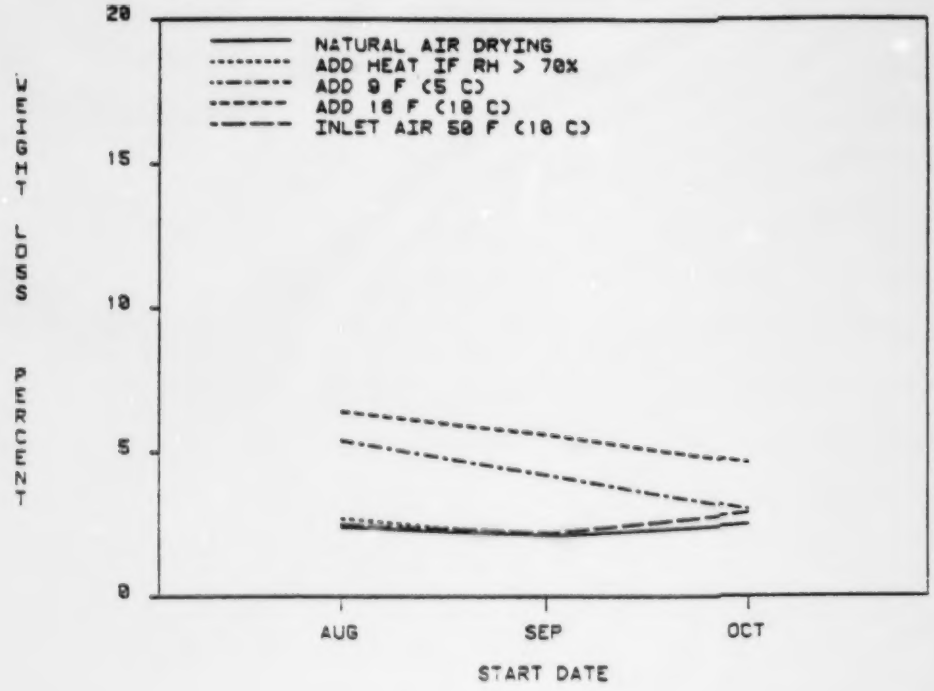

FIGURE 10. Effect of Start Date on Overdrying when "Through Drying". [Airflow Rate: 1 cfm/bu (13 L/s.m^3), Initial Moisture Content: 19%.

As the start date was delayed, overdrying decreased from 6.4 to 4.6% when adding 18°F (10°C) continuously, and from 5.4 to 3.6% when adding 9°F (5°C) continuously. Higher humidities and cooler ambient temperatures later in the year typically resulted in less overdrying.

8.4.2 Grain Quality: As discussed in the "Computer Simulation Development" section, the existing quality models did not conform to situations on the prairies. The models only assess universal characteristics such as germination, but do not include specific characteristics present in each specialized drying

situation. For the Saskatchewan farmer, the grade of milling wheat is most relevant, as it determines the price of the grain.

The field test results will be discussed here, since grade was measured in all field tests. No grade reduction occurred during the field tests. None of the drying strategies used were very harsh, therefore, no damage due to excessive drying air temperatures was expected. Also, the grain was at a relatively low initial moisture content, and was dried within a reasonable length of time, so no damage due to spoilage was expected either.

8.5 DRYING COST

8.5.1 Cost Components: The various components of the total costs are shown in TABLE 15.

TABLE 15. Effect of Start Date on Total Costs for "Average Drying". [Initial Moisture Content: 19%, Airflow Rate: 1 cfm/bu (13 L/s.m^3)].

START DATE	DRYING STRATEGY	CAPITAL AND REPAIR COST ¢/bu ($/t)	LABOUR COST ¢/bu ($/t)	ENERGY COST Propane ¢/bu ($/t)	ENERGY COST Natural Gas ¢/bu ($/t)	TOTAL COST Propane ¢/bu ($/t)	TOTAL COST Natural Gas ¢/bu ($/t)
August 1	Natural Air	10.6 (3.90)	2.9 (1.07)	2.0 (0.74)	2.0 (0.74)	16 (5.71)	16 (5.71)
	Add Heat if RH >70%	19.7 (7.24)	2.9 (1.07)	2.2 (0.81)	2.0 (0.74)	25 (9.12)	25 (9.05)
	Add 9°F (5°C)	15.9 (5.85)	2.9 (1.07)	4.2 (1.54)	2.2 (0.81)	23 (8.46)	21 (7.73)
	Add 18°F (10°C)	14.1 (5.18)	2.9 (1.07)	5.0 (1.84)	2.2 (0.81)	22 (8.09)	19 (7.06)
September 1	Natural Air	12.8 (4.71)	2.9 (1.07)	3.1 (1.14)	3.1 (1.14)	19 (6.92)	19 (6.92)
	Add Heat if RH >70%	24.6 (9.04)	2.9 (1.07)	3.3 (1.21)	3.1 (1.14)	31 (11.32)	31 (11.25)
	Add 9°F (5°C)	17.4 (6.40)	2.9 (1.07)	5.3 (1.95)	2.8 (1.03)	26 (9.42)	23 (8.50)
	Add 18°F (10°C)	15.0 (5.51)	2.9 (1.07)	6.0 (2.21)	2.6 (0.96)	24 (8.79)	21 (7.54)
October 1	Natural Air	18.1 (6.65)	2.9 (1.07)	5.7 (2.10)	5.7 (2.10)	27* (9.82)	27* (9.82)
	Add Heat if RH >70%	37.7 (13.86)	2.9 (1.07)	8.4 (3.09)	6.5 (2.39)	49* (18.02)	47* (17.32)
	Add 9°F (5°C)	19.6 (7.21)	2.9 (1.07)	6.8 (2.50)	3.6 (1.32)	29 (10.78)	26 (9.60)
	Add 18°F (10°C)	14.8 (5.44)	2.9 (1.07)	5.8 (2.13)	2.5 (0.92)	24 (8.64)	20 (7.43)

* Drying completed in the spring.

Capital and repair costs formed the largest component of total cost. Labour cost was the same in all cases as monitoring the bin

and mixing the bin after drying was common to all drying strategies. Energy cost was not a large component of the total cost in most cases. For this reason, using natural gas did not appear to be a major advantage in this situation. Propane is the fuel used by farmers and the same basic trend will be shown by propane that would be shown by natural gas. Therefore, only propane will be discussed in the following section.

However, because capital cost is such a large component, it's important to review the procedures used to determine the values. It was necessary to determine a typical lifetime for the equipment. Discussion with researchers, manufacturers, and farmers indicated that a 10 year lifetime was typical if operating for 3 weeks per year for the heater and fan. For the distribution system, they indicated a 20 year lifetime was typical, regardless of amount of operation.

The above analysis rates the heater and fan lifetime at 5040 hours of operation. To calculate the capital cost component of total drying cost, the operating time for each run entered the calculation. Thus a run that took only 10 days would be less costly than a run that took 40 days. Some economists base the capital cost component on the yearly lifetime regardless of operational hours per year. However, we feel our procedure to be more valid. It accounts for very short runs where farmers may be able to use their equipment more than once a year and spread out the capital cost over a number of runs. It also increases the capital cost component if farmers operate their equipment for higher than typical time each year as their equipment may not last 10 years.

The high capital cost component also indicates the value of equipment maintenance. Operators who don't maintain their equipment will have higher drying costs because the equipment lifetime will be reduced. Conversely, conscientious operators will decrease their drying costs.

8.5.2 Effect of Initial Moisture Content: Drying cost as affected by initial moisture content is given in FIGURE 11.

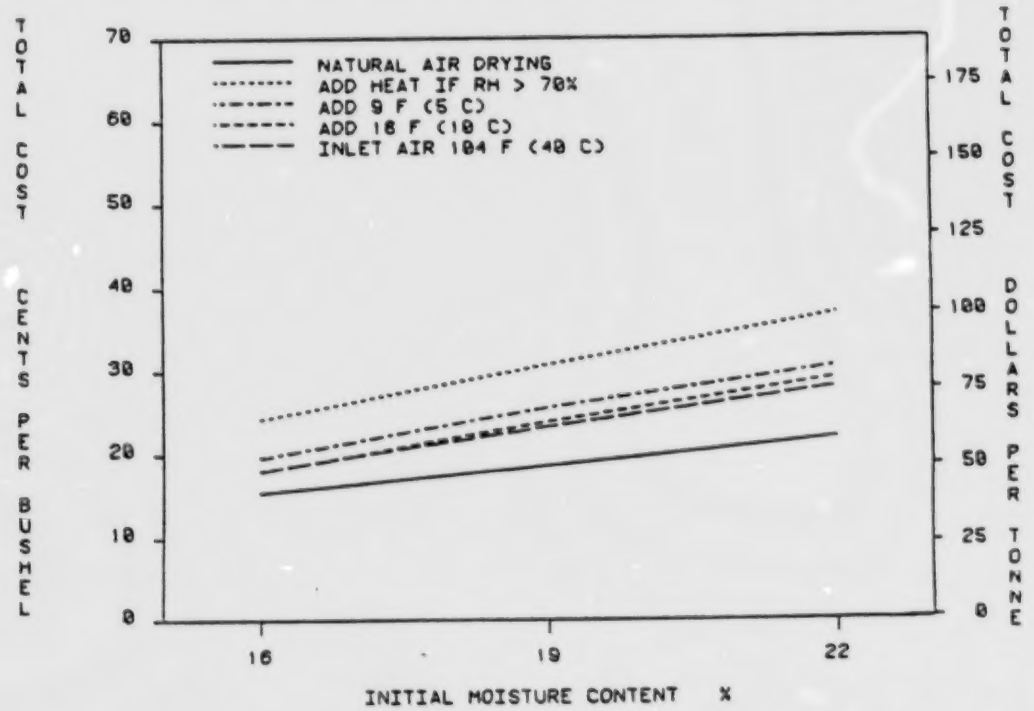

FIGURE 11. Effect of Initial Moisture Content on Drying Cost. [Start Date: Sept. 1, Airflow Rate: 1 cfm/bu (13 L/s.m^3)].

As initial moisture content increased, total cost increased. This seemed logical because as initial moisture content increased, the drying time would be longer, and thus capital and energy costs would also increase. However, the drying cost did not increase proportionally with the amount of moisture removal. For example,

natural air drying from 22% required five times more moisture removal than from 16%, but the drying cost only increased from 16 to 22¢/bu ($5.88 to $8.08/t). Thus, drying from higher initial moisture contents is not as costly as expected.

As expected, natural air drying was the cheapest drying method. But, surprisingly, using a humidistat to control the inlet air was the most expensive method. With 19% initial moisture content, cost was 30¢/bu ($11.00/t). Controlling the inlet air at 104°F (40°C) and continuously adding 18°F (10°C) were the cheapest. Respective costs were 23 and 24¢/bu ($8.44 and $8.81/t). It appears that if a heater is purchased, it is cost advantageous to add at least 18°F (10°C). By adding more heat, the decreased operating time drops the capital cost component even though the energy cost component is increased. Since the purchase cost is the largest, the overall effect is reduced total cost.

8.5.3 Effect of Start Date: The total drying cost as affected by the start date is given in FIGURE 12.

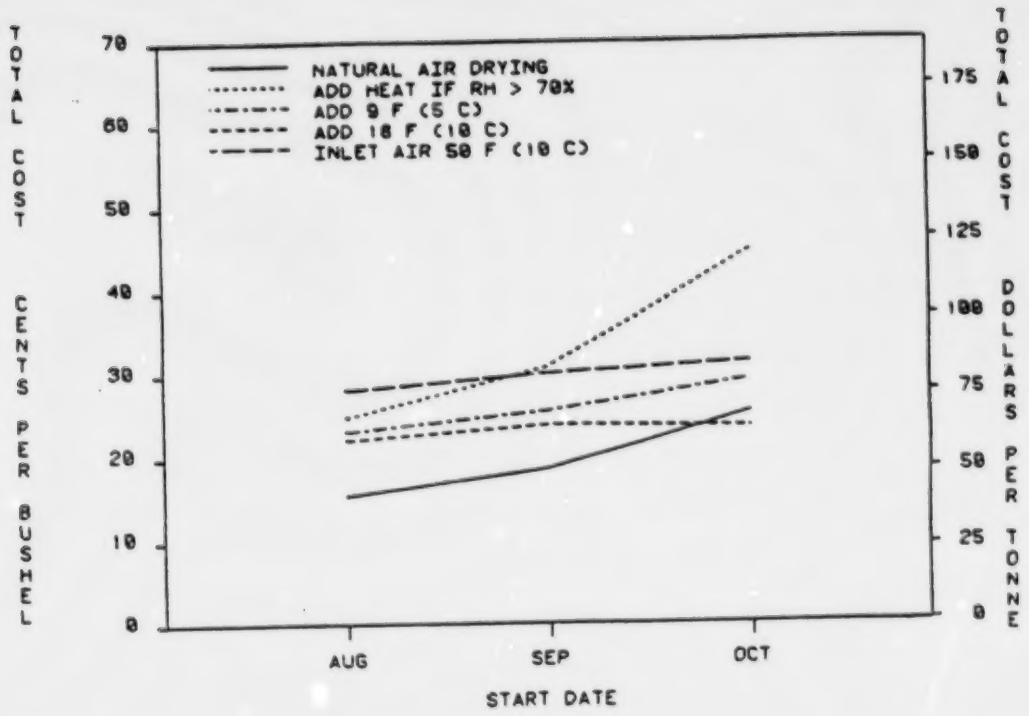

FIGURE 12. Effect of Start Date on Total Drying Cost. [Initial Moisture Content: 19%, Airflow Rate: 1 cfm/bu (13 L/s.m^3)].

Costs increased as the start date was delayed. With natural air drying, the increase was gradual from August to September, but increased greatly in October as drying was not completed in the fall. Costs were 16, 19, and 25¢/bu ($5.88, $6.98, and $9.19/t). However, when adding 9 or 18°F (5 or 10°C) of heat, the gradual increase continued in October. Respective costs were 22, 24, and 24¢/bu ($8.08, $8.82, and $8.82/t). As before, adding 18°F (10°C) was the least costly of the "adding heat" strategies. In October, adding 18°F (10°C) was over 1¢/bu ($0.37/t) cheaper than natural air drying.

8.5.4 Effect of Airflow Rate on Total Cost: August

Total cost as affected by airflow rate in August is given in FIGURE 13.

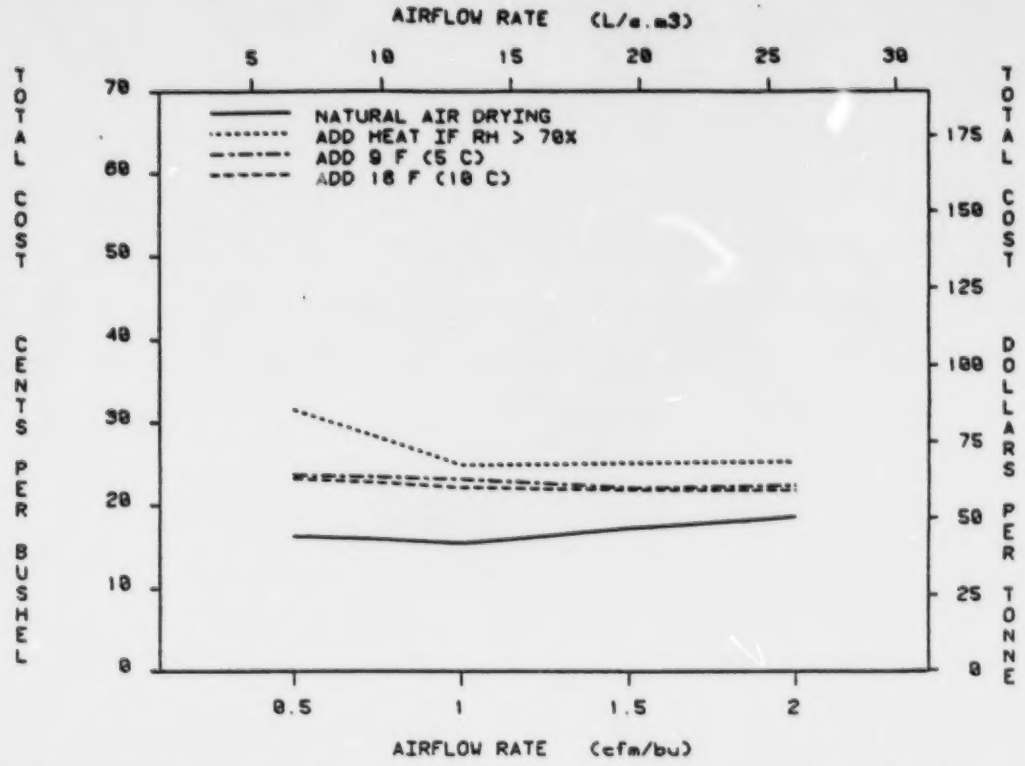

FIGURE 13. Effect of Airflow Rate on Total Drying Cost in August. [Initial Moisture Content: 19%].

Airflow rates had very little effect on total cost in August. When natural air drying, the costs only ranged from 16 to 19¢/bu ($5.88 to $6.98/t). Natural air drying, when adding 18°F (10°C), the drying costs only ranged from 22 to 23¢/bu ($8.08 to $8.45/t). As the airflow rate increased, energy costs increased, but because the drying time was reduced, capital costs decreased by similar amounts.

October

Total cost as affected by airflow rate in October is given in FIGURE 14.

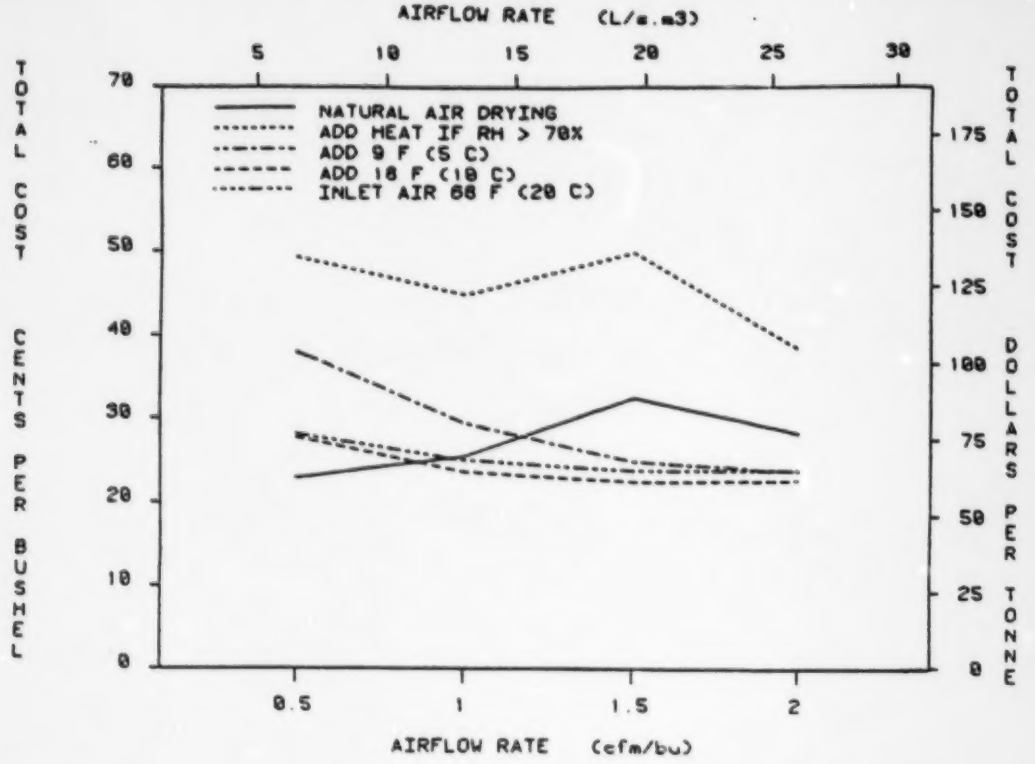

FIGURE 14. Effect of Airflow Rate on Total Drying Cost in October. [Initial Moisture Content: 19%].

In October, the effect of airflow rate was not consistent. When natural air drying, the costs generally increased as airflow rate increased. The rate of increase was more than in August. This is likely because in October, the poorer drying conditions decrease drying effectiveness and hence increase capital cost. When constantly adding heat, the costs decreased as airflow rate increased.

At 1 cfm/bu (13 L/s.m^3), the natural air drying costs were about equal to continuously adding 18°F (10°C). At higher airflow rates, adding heat was more economical, and vice versa. However, since most systems typically deliver about 1 cfm/bu (13 L/s.m^3), it appears that economics does not favour one method over the other.

Thus, farmers can use other criteria to select their strategy. Natural air drying in October at typical airflow rates was not completed in the fall. So the wet grain had to be monitored during the winter, it could not be sold "dry", and drying had to be completed in the spring. When adding heat, overdrying was increased and an extra piece of equipment, the heater, must be operated. However, drying will be completed in the fall. Using this information, the drying strategy decision of different operators will likely vary, depending on which best suits the specific operation.

The strategy of holding the inlet air at various constant temperatures had been investigated, but did not seem to have any real benefits over adding a constant amount of heat. For example, at 1 cfm/bu (13 L/s.m^3), adding 18°F (10°C) cost 24¢/bu ($8.82/t) while holding the inlet air at 68°F (20°C) cost 25¢/bu ($9.19/t). Holding inlet air temperature constant also has a further disadvantage since it would require more complex controls than presently exist on any known supplemental heaters. These results indicate that such controls would not be beneficial.

8.5.5 **Effect of "Average" vs "Through Drying"**: The total cost increase due to "through drying" as affected by initial moisture content is given in FIGURE 15.

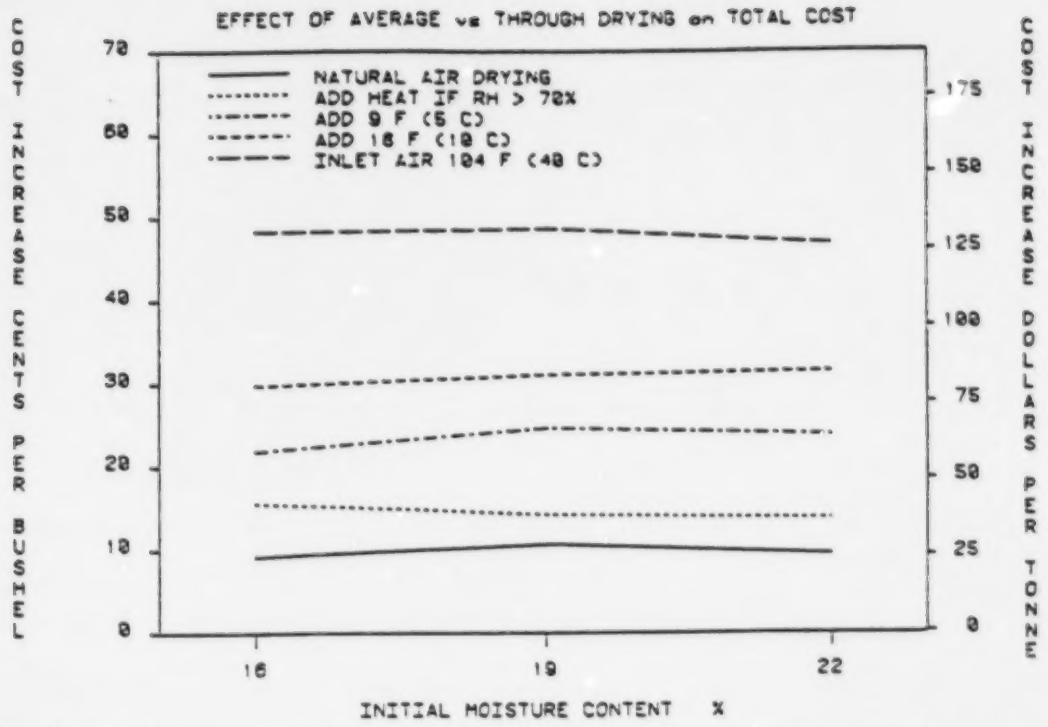

FIGURE 15. Increase in Drying Cost due to "Through Drying". [Start Date: Sept. 1, Airflow Rate: 1 cfm/bu (13 L/s.m^3)].

It cost up to 50¢/bu ($19.85/tonne), more when the grain was "through dried" instead of "average drying". Even when natural air drying, the extra drying costs were 9¢/bu ($3.31/t). This reinforces the benefit of "average drying" and mixing, especially when continuously adding heat as drying costs become prohibitive.

Less overdrying was noted when controlling the humidity at 70%. Because the heater would not be operating at all times, the average humidity going into the bin would probably be higher when using a humidistat than if continuous heat was being used. This would explain the lower overdrying cost when using a humidistat. However, overdrying when using a humidistat was slightly higher than natural air drying. In all cases, "through drying" was more costly than "average drying".

8.6 EASE OF OPERATION AND ADJUSTMENT

Ease of operation is difficult to simulate. The results that were determined in field testing provide all necessary information and should be refered to.

8.7 IMPLICATIONS OF RESULTS ON HARVESTING AND DRYING STRATEGY

Although factors such as drying time, energy, and quality will all affect the selected strategy, the most relevant factor is economics. With the trends of these results, it would be advantageous to harvest early in the year at low initial moisture contents and to use properly sized natural air drying without supplemental heat. (Early harvest would also result in the additional benefit of reduced field losses, although no specific values are available in research.) Unfortunately, early in the year, initial grain moisture content is typically high. Since drying costs don't increase greatly with initial moisture content and since delayed start dates increase drying costs (especially if supplemental heat or spring drying is required), it appears that early harvest is the most logical choice, even if drying higher initial moisture contents. Previous research by Lischynski (1986) indicates that 20% is an upper practical limit for natural air drying of cereals as spoilage may occur at higher moisture contents.

To minimize the chance of not completing drying in the fall or of requiring supplemental heat, higher airflow rates are sometimes proposed. Airflow rates of 2 cfm/bu (26 $L/s.m^3$) would typically dry grain even if started on October 1. With 2 cfm/bu (26 $L/s.m^3$) instead of 1 cfm/bu (13 $L/s.m^3$), costs were similar in August but considerably higher in October. Furthermore, extremely large fans

would be required which may not be feasible as most farms have limited electrical capacity. Also, in some wet falls conditions where no drying occurs, the fan size would have no effect.

A more logical approach seems to be sizing the fans to 1 cfm/bu (13 L/s.m^3), and beginning drying as early as possible. By drying early in the fall, the maximum benefits of low cost natural air drying could be captured. Some drying would still likely have to occur in October type weather. To handle this, operators could either rely on natural air drying and complete drying in the spring, or purchase the minimum amount of heaters required to complete drying in the fall. With a minimum of heaters as backup, capital cost is minimized and the hassle of spring or custom drying is eliminated. Economically, both options are similar so the operator's selection should best suit their situations.

For operators who select heaters, it's difficult to determine simple guidelines about their use. However, the following recommendations seem logical:

When to start heaters: In this report, it appeared that October 1 is a logical start time for typical Saskatoon conditions. However, few years are typical and other areas of the province also require guidelines. So a start time that's determined by actual weather may be more practical than a specific date. Air temperature and relative humidity are the two relevant weather factors. Of the two, air temperature was the most critical because the high humidities usually occur when low temperatures have already necessitated supplemental heat. A start temperature is required that doesn't lead to heaters operating prematurely, yet is early

enough to complete drying in the fall. Starting the heater when night temperatures drop into the 41 to 32°F (5 to 0°C) range should achieve this. This is the principle guideline for time to start "adding heat".

Occasionally, humidities will rise above 70%, in warm conditions for extended periods. If a heater is available, adding as little as 9°F (5°C) will sufficiently reduce humidities to allow drying to progress. Conversely, if no heater is available and if more drying weather is expected, the fan may be shut off until good weather recurs (provided the grain is cool and at a low moisture content).

The location and time of year may also affect start time. For example, if a harvest is delayed to October in northern parts of the province, operators may start adding heat even if conditions are favorable as drying very seldom occurs naturally in November. Conversely, if a cool spell occurs in September in the south, operators may delay heater startup as warm weather will still likely occur.

How much heat to add: It appears that adding 18°F (10°C) is a logical recommendation. This provides enough heat to keep costs down, yet it should avoid spoilage, extreme overdrying, and the need for very large heaters. Only if outside temperatures drop below 23°F (-5°C) will more heat likely be required to keep inlet air temperatures high enough for productive drying. Conversely, if daily high temperatures exceed 59°C (15°C), operators can shut off their heaters to reduce overdrying and decrease the risk of spoilage.

If the heater has a controller, supervision can be reduced by

using the controller to maintain the desired heating strategy. However, if no controller is available, constantly adding 18°F (10°C) is a worthwhile strategy.

If an operator has to speed up drying, for a reason such as a very late harvest, more than 18°F (10°C) can be added, but the operation should be cautiously monitored.

When to shut off heaters and spring dry: In some cases, when the weather gets too cold in the fall, supplemental heaters may not be adequate to warm the air enough. In these cases, the heaters should be shut off when an average air inlet temperature of 41 to 50°F (5 to 10°C) cannot be maintained. At this time, the grain should be cooled to a safe storage temperature, and the drying completed in the spring.

Required number of heaters: The number of required heaters to have will depend on the climate and each farmer situation. Each farmer can determine this by using the above recommended practices of early harvest with adequate fans to minimize the required heaters, and then purchase the required amount when they are needed. It's anticipated that the number will range from about one for every two or three fans in the north, to one for every five or six fans in the south. However, each farmer should determine their own requirements.

APPENDIX I

TERMINOLOGY

Airflow - Volume of air movement per unit time expressed in cubic feet per minute (cfm) (litres per second (L/s)).

Airflow Rate - Airflow per unit of grain expressed in cubic feet per minute (cfm) per bushel (bu) of grain (litres per second (L/s) per cubic metre (m^3) of grain).

Average Dry - Refers to a bin of grain that has been natural air dried in which the average of all the grain is dry even though some of the grain may be overdry while other grain may be wet.

Computer Simulation - Use of mathematical models to calculate results of a drying process.

Dry - The maximum moisture content which the Canadian Grain Commission accepts without considering the grain tough or damp. For wheat, dry is 14.5% moisture content.

Drying Front - Location in grain mass at which drying is occurring. Grain below the drying front is at equilbrium with the inlet air. Grain above the drying front is at the initial moisture content.

Inlet Air Temperature - Temperature of air entering the drying system after it has passed through the fan and/or burner.

Milling Wheat - Wheat which will be ground up into flour for use in baking.

Mixogram - A test to determine the baking quality of wheat. Flour and water are mixed while measuring the forming characteristics and plotting the results on a graph. Used to determine heat damage in wheat that cannot be detected visually.

Moisture Content - The amount of water as a percentage (%) of the total weight of the dry matter and water. Moisture Content expressed this way is termed "wet basis".

Natural Air Drying - The process of pushing ambient air through a bin of wet grain to lower the moisture content.

Specific Energy Consumption - Is a measure of the energy required to remove a quantity of water from grain and is expressed in British Thermal Units (Btu) of energy per pound (lb) of water removed (kilojoules (kJ) of energy per kilogram (kg) of water removed).

Spring Drying - Completing natural air drying in the spring due to drying not being completed in the fall because of unfavourable weather.

Supplemental Heat - Adding small amounts of heat to natural air drying to reduce inlet air humidity and increase inlet air temperature.

Through Dry - Refers to a bin of grain that has been natural air dried until the top layer of grain is dry.

APPENDIX II

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APPENDIX III

SPECIFICATIONS

BINS:		
- make	Westeel Rosco	Westeel Rosco
- model	148	146
- diameter	13.7 ft (4.2 m)	13.7 ft (4.2 m)
- height to eaves	30 degrees from horizontal	
- filler cap diameter	19.6 in (500 mm)	19.6 in (500 mm)
- manhole size		
- top width	11.8 in (300 mm)	11.8 in (300 mm)
- bottom width	15.7 in (400 mm)	15.7 in (400 mm)
- height	24.4 in (620 mm)	24.4 in (620 mm)
FANS:		
- make	Caldwell	
- model	ILC24-312	
- type	in-line centrifugal	
- size	3 hp (2.2 kW) one phase	
- outlet size	24 in (609 mm)	
BURNERS:		
- make	Caldwell	
- model	ILCH 24-VPGE	
- maximum rating	135,000 Btu/h (142 MJ/h)	
- ignition	spark	
- temperature adjustment	pressure regulator and thermostat	
- type	multi-port on a straight pipe	
PERFORATED FLOORS:	Model 148 Bin	Model 146 Bin
- surface area	117 ft^2 (10.9 m^2)	117 ft^2 (10.9 m^2)
- hole shape	oblong	round
- porosity	5.42 holes/in^2 (0.84 holes/cm^2)	105 holes/in^2 (16.3 holes/cm^2)
- hole size	0.28 x 0.08 in (7 x 2 mm)	0.05 in diameter (1.3 mm) diamter

APPENDIX IV

DETAILED FIELD TEST LAYER MOISTURE CONTENTS

TABLE 16. Run 1 - Average Dry. Dates and Moisture Contents (M.C.).

START DATE		AUGUST 14		
END DATE		AUG. 17	AUG. 21	AUG. 27
SAMPLING LOCATION FROM FLOOR ft	(m)	BIN A M.C. %	BIN B M.C. %	BIN C M.C. %
16	(4.9)	17.2	17.9	17.4
13	(4.0)	17.3	17.3	17.2
10	(3.0)	17.6	17.4	17.1
7	(2.1)	18.1	14.6	14.6
4	(1.2)	10.1	11.4	12.7
1	(0.3)	6.8	10.3	11.8

TABLE 17. Run 2 - Average Dry. Dates and Moisture Contents (M.C.).

START DATE		SEPTEMBER 19		
END DATE		SEPT. 28	SEPT. 28	OCT. 9*
SAMPLING LOCATION FROM FLOOR ft	(m)	BIN A M.C. %	BIN B M.C. %	BIN C M.C. %
16	(4.9)	16.6	17.3	16.3
13	(4.0)	16.5	16.5	16.1
10	(3.0)	15.5	16.0	16.0
7	(2.1)	13.4	14.0	16.2
4	(1.2)	12.8	12.8	15.7
1	(0.3)	12.5	12.3	14.5
* Drying not complete.				

TABLE 18. Run 3 - Average Dry. Dates and Moisture Contents (M.C.).

START DATE		OCTOBER 14		
END DATE		OCT. 28	OCT. 25	NOV. 4*
SAMPLING LOCATION FROM FLOOR ft	(m)	BIN A M.C. %	BIN B M.C. %	BIN C M.C. %
16	(4.9)	17.[illegible]	17.3	17.2
13	(4.0)	16.4	16.2	17.3
10	(3.0)	16.0	16.5	17.1
7	(2.1)	13.8	14.5	16.8
4	(1.2)	12.8	12.5	14.7
1	(0.3)	12.2	11.6	13.3
* Drying not complete.				

TABLE 19. Run 1 - Through Dry. Dates and Moisture Contents (M.C.).

START DATE		AUGUST 14		
END DATE		AUG. 22	AUG. 24	AUG. 31
SAMPLING LOCATION FROM FLOOR ft	(m)	BIN A M.C. %	BIN B M.C. %	BIN C M.C. %
16	(4.9)	17.3	18.2	17.1
13	(4.0)	13.1	14.4	14.1
10	(3.0)	10.2	15.0	14.0
7	(2.1)	7.9	11.4	12.8
4	(1.2)	6.9	10.2	12.4
1	(0.3)	6.3	9.2	12.4

TABLE 20. Run 2 - Through Dry. Dates and Moisture Contents (M.C.).

START DATE		SEPTEMBER 19		
END DATE		OCT. 3	OCT. 1	OCT. 9*
SAMPLING LOCATION FROM FLOOR ft	(m)	BIN A M.C. %	BIN B M.C. %	BIN C M.C. %
16	(4.9)	16.3	17.1	16.3
13	(4.0)	14.1	14.6	16.1
10	(3.0)	13.5	14.8	16.0
7	(2.1)	13.0	13.4	16.2
4	(1.2)	12.8	12.7	15.7
1	(0.3)	12.8	12.5	14.5
* Drying not complete.				

TABLE 21. Run 3 - Through Dry. Dates and Moisture Contents (M.C.).

START DATE		OCTOBER 17		
END DATE		OCT. 31	OCT. 28	NOV. 4*
SAMPLING LOCATION FROM FLOOR ft	(m)	BIN A M.C. %	BIN B M.C. %	BIN C M.C. %
16	(4.9)	17.0	17.0	17.2
13	(4.0)	14.7	14.0	17.3
10	(3.0)	14.2	14.7	17.1
7	(2.1)	12.9	12.5	16.8
4	(1.2)	12.5	11.3	14.7
1	(0.3)	12.2	11.6	13.3
* Drying not complete.				

APPENDIX V

WEATHER DATA.

TABLE 22. Run 1 - Weather Data.

DATE	MINIMUM TEMPERATURE °F (°C)	MAXIMUM TEMPERATURE °F (°C)	MINIMUM RELATIVE HUMIDITY %	MAXIMUM RELATIVE HUMIDITY %
Aug. 14	63.0 (17.2)	82.9 (28.3)	43	81
15	55.4 (13.0)	72.9 (22.7)	40	91
16	49.6 (9.8)	63.0 (17.2)	55	92
17	45.7 (7.6)	77.9 (25.5)	45	90
18	56.8 (13.8)	86.4 (30.2)	43	88
19	52.9 (11.6)	72.0 (22.2)	48	81
20	46.2 (7.9)	66.6 (19.2)	48	94
21	47.8 (8.8)	80.1 (26.7)	37	79
22	46.9 (8.3)	69.1 (20.6)	48	92
23	50.2 (10.1)	85.3 (29.6)	41	74
24	56.5 (13.6)	79.3 (26.3)	49	70
25	44.8 (7.1)	57.7 (14.3)	56	81
26	42.8 (6.0)	63.0 (17.2)	53	87
27	48.7 (9.3)	73.0 (22.8)	49	82
28	52.3 (11.3)	83.5 (28.6)	41	75

TABLE 23. Run 2 - Weather Data.

DATE	MINIMUM TEMPERATURE °F (°C)	MAXIMUM TEMPERATURE °F (°C)	MINIMUM RELATIVE HUMIDITY %	MAXIMUM RELATIVE HUMIDITY %
Sept. 19	48.2 (9.0)	54.7 (12.6)	60	86
20	46.0 (7.8)	54.7 (12.6)	79	91
21	49.1 (9.5)	51.1 (10.6)	90	98
22	48.4 (9.1)	58.6 (14.8)	65	96
23	43.9 (6.6)	59.0 (15.0)	70	100
24	47.5 (8.6)	64.4 (18.0)	66	92
25	44.2 (6.8)	50.5 (10.3)	87	100
26	46.6 (8.1)	56.8 (13.8)	67	92
27	45.3 (7.4)	63.0 (17.2)	60	100
28	39.9 (4.4)	60.1 (15.6)	59	100
29	40.1 (4.5)	50.9 (10.5)	71	94
30	36.5 (2.5)	55.9 (13.3)	58	100
Oct. 1	41.9 (5.5)	50.5 (10.3)	67	100
2	33.1 (0.6)	40.8 (4.9)	72	100
3	29.3 (-1.5)	46.4 (8.0)	81	100
4	35.1 (1.7)	48.4 (9.1)	68	99
5	27.5 (-2.5)	46.4 (8.0)	82	100
6	42.8 (6.0)	65.7 (18.7)	66	100
7	37.2 (2.9)	53.2 (11.8)	69	93
8	27.0 (-2.8)	36.3 (2.4)	86	100

TABLE 24. Run 3 - Weather Data.

DATE	MINIMUM TEMPERATURE °F	(°C)	MAXIMUM TEMPERATURE °F	(°C)	MINIMUM RELATIVE HUMIDITY %	MAXIMUM RELATIVE HUMIDITY %
Oct. 17	49.1	(9.5)	69.4	(20.8)	54	77
18	39.0	(3.9)	66.4	(19.1)	49	84
19	37.4	(3.0)	63.3	(17.4)	41	84
20	39.4	(4.1)	66.0	(18.9)	49	84
21	40.1	(4.5)	63.0	(17.2)	49	88
22	42.1	(5.6)	57.7	(14.3)	55	75
23	36.9	(2.7)	63.5	(17.5)	48	87
24	37.8	(3.2)	66.2	(19.0)	45	76
25	36.9	(2.7)	60.4	(15.8)	59	86
26	36.3	(2.4)	62.8	(17.1)	49	82
27	40.8	(4.9)	63.5	(17.5)	54	75
28	31.5	(-0.3)	38.7	(3.7)	73	100
29	24.4	(-4.2)	36.0	(2.2)	97	100
30	26.6	(-3.0)	36.9	(2.7)	86	100
31	15.1	(-9.4)	25.2	(-3.8)	100	100
Nov. 1	13.3	(-10.4)	27.9	(-2.3)	100	100
2	17.2	(-8.2)	36.0	(2.2)	100	100
3	20.3	(-6.5)	34.2	(1.2)	89	100
4	34.2	(1.2)	41.0	(5.0)	87	91

APPENDIX VI

NATURAL AIR DRYING SIMULATION MODEL EQUATIONS

I. DRYING TEMPERATURE

Thompson (1968) proposed a drying temperature based on sensible heat balance between the air and the grain at each layer:

$$Te = \frac{(.24) + .45\ HO)\ t0 + C\ Ge}{.24 + .45\ HO + C} \qquad I.1$$

Where C is the specific heat of grain expressed as BTU/LB of air:

$$C = (.35 + M)\ R \qquad I.2$$

where

$$R = Pd\ /\ m\ dt \qquad I.3$$

Units are as follows: air temperature entering the layer, t0 in F; dry matter in the layer, Pd in LBS; mass flowrate of the air, m in LBS/hr; and time step for simulation, dt in hours; HO and Ge are humidity ratio and grain temperatures in LB/LB and F respectively, and M is moisture content decimal dry basis.

II. EQUILIBRIUM MOISTURE CONTENT

The equilibrium moisture content (Me) of the grain at each layer is evaluated at Te and HO using the Henderson-Thompson equation and the constants reported by Vermuganti and Pfost (1980):

$$Me = \left[\frac{\ln(1 - rh)}{-K\ (Te + C)} \right]^{1/N} /100 \qquad II.1$$

where:

	K	N	C
Corn	1.875E-5	2.120	164.690
Barley	5.045E-5	1.958	70.430
Wheat	2.301E-5	2.286	55.815
Rapeseed	14.330E-5	1.723	146.560

Te is in C, and Me is decimal dry basis.

III. DRYING RATE EQUATIONS

Drying rate equations have the following basic form:

$$\frac{dM}{dt} = -K\,(M - Me) \qquad \text{III.1}$$

where K is a drying constant and can be found from:

Corn: $$K = 6.272\,Ps^{.772}\,(v / 0.859)^{.8} \qquad \text{III.2}$$

(Source: Sabbah et al, 1979)

Ps is saturation vapor pressure in g/cm2, and v is air velocity in m/s.

Barley: $$K = 18.4 \exp\left(\frac{-200}{T + 13}\right) \qquad \text{III.3}$$

T is in C.

(Source: Bowden et al, 1983)

Wheat $$K = 1.05\left[18.4 \exp\left(\frac{-200}{T + 13}\right)\right] \qquad \text{III.4}$$

Rapeseed: $$K = .00027\,T + .004 \qquad \text{III.5}$$

T is in C.

(Source: Singh et al. 1983)

IV ABSORPTION RATE EQUATION

Absorption of moisture occurs when the moisture in the grain is below the corresponding relative humidity in the air. The following equations are proposed:

For Corn:

$$MR = \exp(-.625\,Ps^{.466\,rh}\,rh^{3}\,t) \qquad \text{IV.1}$$

Ps is the saturated vapor pressure in psi, and t is in hours.

For wheat, the following equation which has been developed for heads was used:

$$MR = \exp(-K\,t^{N}) \qquad \text{IV.2}$$

$$K = \exp(-5.06459 + .436285 \ln(T) + .04886\,Mi)$$

$$N = 1.51817 - 5.508018E\text{-}3\,rh$$

(Source: Duggal et al., 1982)

For barley and rapeseed we could not find a relationship.

V. CONDENSATION

A procedure suggested by Roth and Bakker (1973) was used. The method is shown in Fig. V.1. H and T are the infeasible humidity ratio and temperature of the cooled air. The new conditions after condensation (Hf and Tf) are the intersection value of constant enthalpy line and the approximated saturation line (^{TM} 100 % RH).

Equation for constant enthalpy line is:

$$e = 1006\ Tf \text{ and } Hf\ (2502000 + 1775\ Tf) \qquad V.1$$

The value of e is found by inserting the current values of H and T in V.1.

Fig. V.1 Estimating the new point after condensation.

Equation for the saturation line has the following form:

$$\frac{Hf - Hs}{Tf - Ts} = \frac{Hs - H'}{Ts - T'} = \text{slope} \qquad V.2$$

$Ts - T' = 1$ C, and $Ts = T$

Equations V.1 and V.2 are solved simultaneously to find Tf and Hf.

VI. PSYCHROMETRICS

The psychrometric routines needed for this simulation are saturated vapor pressure, specific volume, relative humidity and humidity ratio. The equations given in the ASAE (1983) were used.

VII. FINAL TEMPERATURE OF GRAIN

After computing moisture loss for each layer, the new humidity ratio and grain temperature are calculated using following equations:

$$Hf = HO + dM\ R \qquad VII.1$$

$$Gf = \frac{(0.24 + 0.45\ HO)\ Te - dH\ (1060.8 + L + 32 - Te) + C\ Te}{0.24 + 0.45\ Hf + C} \qquad VII.2$$

where dH = (Hf - HO) in LB/LB, L is heat of vaporization in BTU/LB.

APPENDIX VII

COMPUTER SIMULATION COST ASSUMPTIONS AND RESULTS

TABLE 25. The Price of Various Fuels (Energy Sources) Used in Simulations.

Electricity:

3600 kJ per KWh at 4.5¢/kWh - $0.0125/MJ

Natural Gas:

37 080 KJ per m^3 at 12.89¢/m^3 - $0.0035/MJ

Propane:

Propane is sold in liquid form. To calculate heat contents of a litre of propane in liquid form:

Density of liquid = 489 kg/m^3.
Density of vapor = 1.875 kg/m^3.

88 433 KJ/m^3 of vapor - 88 433/1.875 x 489 = 23 063 327 kJ per m^3 of liquid - 23 063 kJ per L of liquid propane.

Price at 26.4¢/L - $0.0115/MJ

TABLE 26. Prices and Rates for Cost Analysis.

Purchase price of bin floor	$700
Purchase price of fan	($1,000) (cfm/bu)$^{0.6}$ [$1,000 x (L/s.$m^3$/13)]$^{0.6}$
Purchase price of heater	$1,200
Purchase price of humidistat/thermostat controller	$175
Bin floor service life	20 yrs
Fan, heater, controller service life	5040 hours of use (10 yrs @ 3 wks/yr normal use)
Resale value	10% of original price
Interest rate	7% per annum
Repair and insurance cost	1% of purchase cost
Wheat prices:	
- 1 CWRS	$127/tonne
- Canada feed	$90/tonne
Energy cost:	
- electricity	4.5¢/kWh
- propane	26.4¢/L
- natural gas	12.89¢/m^3

Column Description

A - Initial Moisture Content (decimal).

B - Continuous Heat Temperature Rise (°C).

C - Thermostat Control Temperature (°C).

D - Humidistat Control Humidity (%).

E - Airflow Rate (cfm/bu).

F - Average Final Grain Temperature (°C).

G - Average Final Moisture Contnet (%).

H - Standard Deviation of Average Final Moisture Content.

I - Heat Energy Consumption (Btu x 10^{-3}).

J - Electrical Energy Consumption (kWh).

K - Specific Energy Consumption (kJ/kg).

L - Weight Loss Due to Overdrying (kg).

M - Drying Time (hrs).

N - Storage Index.

O - Standard Deviation of Storage Index.

P - Incidence Probability of Damaging Rain or Frost.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Drying/Drye Sptemeber 1														-	
Drying using unheated air:														-	
0.16	0	0	0	0.5	7.4	14.5	-	0	323	1404	712	0	0.13	-	0.25
0.16	0	0	0	1	17.5	14.5	-	0	768	3302	376	0	0.07	-	0.25
0.16	0	0	0	1.5	6.6	14.5	-	0	1320	5755	268	0	0.05	-	0.25
0.16	0	0	0	2	10.4	14.5	-	0	1839	7856	200	0	0.04	-	0.25
0.16	0	0	0	1	7.8	13.1	-	0	1454	3340	712	742	0.11	-	0.25
0.16	0	0	0	1.5	8.6	13.1	-	0	2384	5280	484	800	0.07	-	0.25
0.16	0	0	0	2	20.1	12.4	-	0	3494	6435	380	1129	0.06	-	0.25
0.19	0	0	0	1	13	14.5	-	0	1185	1712	580	0	0.28	-	0.25
0.19	0	0	0	1.5	18	14.4	-	0	1871	2695	380	0	0.21	-	0.25
0.19	0	0	0	2	12	14.5	-	0	2758	4008	300	0	0.15	-	0.25
0.19	0	0	0	1	5.5	12.5	-	0	1806	1870	884	1001	0.31	-	0.25
0.19	0	0	0	1.5	13.4	12.3	-	0	3034	3021	616	1140	0.22	-	0.25
0.19	0	0	0	2	10.2	12.4	-	0	4119	4187	448	1066	0.17	-	0.25
0.22	0	0	0	1	14	14.4	-	0	1602	1390	784	0	0.63	-	0.25
0.22	0	0	0	1.5	13.3	14.5	-	0	2561	2226	520	0	0.48	-	0.25
0.22	0	0	0	1.5	8	12.4	-	0	3467	2429	704	1013	0.50	-	0.25
0.22	0	0	0	2	15.6	12.1	-	0	5039	3386	548	1230	0.38	-	0.25
														-	
Undried														-	
0.19	0	0	0	0.5	6.5	15.6	-	0	490	935	1080	0	0.51	-	0.25
0.19	0	0	70	0.5	7.1	15.3	-	1136	490	1235	1080	0	0.50	-	0.25
0.22	0	0	0	0.5	6.1	17.8	-	0	490	733	1080	0	1.04	-	0.25
0.22	0	0	70	0.5	6.7	17.4	-	1136	490	976	1080	0	1.06	-	0.25
0.22	0	10	0	0.5	9.1	15.7	-	4504	490	1112	1080	0	1.06	-	0.25
														-	
Dried with supplemental heat:														-	
0.19	5	0	0	0.5	14.8	14.5	-	5300	286	1128	632	0	0.44	-	0.25
0.19	0	0	50	0.5	12.5	14.5	-	4124	350	1683	772	0	0.46	-	0.25
0.19	0	10	0	0.5	8.8	14.5	-	2876	415	1212	916	0	0.48	-	0.25
0.22	5	0	0	0.5	9.1	14.5	-	7432	403	953	888	0	1.10	-	0.25
0.22	0	15	0	0.5	12	14.5	-	7848	421	998	928	0	1.08	-	0.25
0.22	0	0	50	0.5	10.1	14.8	-	6608	490	1107	1080	0	1.10	-	0.25
														-	

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Drying date September 1															
0.19	0	0	0	1	13	14.5	2.5	0	1185	1720	580	0	0.28	0.11	0.25
0.19	0	40	0	1	24.6	14.4	6.3	10212	212	4528	104	0	0.23	0.1	0.25
0.19	10	0	0	1	17.5	14.5	4.4	7333	441	3762	216	0	0.21	0.1	0.25
0.19	0	0	0	1	5.5	12.5	0.8	0	1806	1872	884	997.7	0.31	0.13	0.25
0.19	0	0	70	1	11.2	14.5	2.4	576	1144	1896	560	0	0.27	0.11	0.25
0.19	0	0	70	1	12.9	12.6	0.8	809	1749	2061	856	990.9	0.3	0.13	0.25
0.19	10	0	0	1	18.1	9.1	1.5	16001	972	3986	476	2635	0.28	0.16	0.25
0.19	0	40	0	1	38.7	5.3	1.4	28772	613	4774	300	4345	0.38	0.23	0.25
0.16	0	0	70	1	--	14.5	--	609	702	3802	344	0	0.06	--	0.25
0.16	10	0	0	1	--	14.4	--	3466	204	5144	100	0	0.03	--	0.25
0.16	5	0	0	1	--	14.5	--	2866	343	5124	168	0	0.04	--	0.25
0.16	0	40	0	1	--	14.4	--	4926	98	6153	48	0	0.03	--	0.25
0.22	0	0	70	1	--	14.5	--	788	1544	1546	756	0	0.67	--	0.25
0.22	10	0	0	1	--	14.4	--	10800	653	3311	320	0	0.54	--	0.25
0.22	5	0	0	1	--	14.5	--	7616	907	2728	444	0	0.58	--	0.25
0.22	0	40	0	1	--	14.5	--	15018	318	4118	156	0	0.61	--	0.25
0.22	0	0	0	1	--	13.3	--	0	2435	1850	1192	611	0.72	--	0.25
0.16	0	0	70	1	--	12.9	--	1084	1405	3702	688	841	0.10	--	0.25
0.22	0	0	70	1	--	13.3	--	1699	2239	2094	1096	580	0.70	--	0.25
0.16	10	0	0	1	--	9.8	--	12401	752	4895	368	2400	0.07	--	0.25
0.22	10	0	0	1	--	8.7	--	19334	1171	3595	576	2726	0.66	--	0.25
0.16	5	0	0	1	--	11.3	--	7600	923	4590	452	1645	0.07	--	0.25
0.22	5	0	0	1	--	10.4	--	12308	1471	3012	720	1943	0.65	--	0.25
0.19	0	0	0	1	--	14.5	--	0	1185	1721	580	0	0.28	--	0.25
0.19	5	0	0	1	--	14.5	--	5400	653	3250	320	0	0.21	--	0.25
0.19	0	10	0	1	--	14.5	--	2216	1021	2423	500	0	0.26	--	0.25
0.19	0	0	70	1	--	14.5	--	576	1144	1897	560	0	0.27	--	0.25
0.19	0	0	0	1	--	13.1	--	0	1454	1636	712	742	0.11	--	0.25
0.19	0	10	0	1	--	12.4	--	3200	1593	2583	780	1052	0.29	--	0.25
0.19	0	0	70	1	--	12.6	--	808	1749	2062	856	991	0.30	--	0.25
0.19	5	0	0	1	--	10.5	--	10264	1250	3446	612	1974	0.27	--	0.25
0.16	0	0	40	1	--	5.9	--	23939	506	5349	248	4236	0.09	--	0.25
0.19	0	0	40	1	--	5.3	--	28772	613	4774	300	4345	0.38	--	0.25
0.22	0	0	40	1	--	5.1	--	32459	702	4398	344	4235	0.84	--	0.25
0.19	0	10	0	1	--	12.4	--	3202	1593	2583	780	1052	0.29	--	0.25

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Drying date August 1 :															
Dried using unheated air															
0.16	0	0	0	0.5	18.2	14.4	-	0	181	763	400	0	0.18	-	0.20
0.16	0	0	0	1	19.4	14.5	-	0	523	2246	256	0	0.11	-	0.20
0.16	0	0	0	1.5	19.4	14.4	-	0	610	2541	124	0	0.06	-	0.20
0.16	0	0	0	2	14.9	14.5	-	0	698	3038	76	0	0.04	-	0.20
0.16	0	0	0	0.5	7.1	13.1	-	0	457	1056	1008	733	0.27	-	0.20
0.16	0	0	0	2	19.5	12.9	-	0	2023	4290	220	872	0.07	-	0.20
0.16	0	0	0	1.5	22.2	12.6	-	0	1596	3109	324	1022	0.11	-	0.20
0.16	0	0	0	1	20.7	11.9	-	0	1038	1698	508	1374	0.15	-	0.20
0.19	0	0	0	1	20.6	14.5	-	0	768	1113	376	0	0.16	-	0.20
0.19	0	0	0	0.5	12.1	14.5	-	0	428	620	944	0	0.29	-	0.20
0.19	0	0	0	1.5	15.1	14.5	-	0	1320	1905	268	0	0.15	-	0.20
0.19	0	0	0	2	18.1	14.4	-	0	1802	2592	196	0	0.11	-	0.20
0.19	0	0	0	1	18	12.2	-	0	1275	1265	624	1149	0.22	-	0.20
0.19	0	0	0	2	23.1	11.9	-	0	2869	2737	312	1297	0.14	-	0.20
0.19	0	0	0	1.5	19.1	10.9	-	0	2029	1712	412	1789	0.19	-	0.20
0.22	0	0	0	1	22.4	14.5	-	0	1070	931	524	0	1.14	-	0.20
0.22	0	0	0	1.5	20.3	14.4	-	0	1714	1481	348	0	0.80	-	0.20
0.22	0	0	0	2	18.1	14.4	-	0	2427	2097	264	0	0.60	-	0.20
0.22	0	0	0	1	13.6	12.5	-	0	1569	1107	768	972	1.23	-	0.20
0.22	0	0	0	1.5	24.8	11.1	-	0	2561	1593	520	1663	0.85	-	0.20
0.22	0	0	0	2	23.7	10.9	-	0	3421	2112	372	1705	0.64	-	0.20
														-	
Undried														-	
0.22	0	0	0	0.5	13.8	15.9	-	0	490	517	1080	0	1.89	-	0.20
0.22	0	10	0	0.5	14.3	15.5	-	980	490	673	1080	0	1.90	-	0.20
0.22	0	0	70	0.5	13.9	15.4	-	1016	490	672	1080	0	1.92	-	0.20
														-	
Dried using supplemen														-	
0.22	5	0	0	0.5	18.3	14.5	-	6100	330	780	728	0	1.85	-	0.20
0.22	0	0	50	0.5	14.3	14.5	-	5080	394	843	868	0	1.95	-	0.20
0.22	0	15	0	0.5	14	14.5	-	3436	479	846	1056	0	1.93	-	0.20

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Drying date August 1															
0.19	0	0	0	1	20.6	14.5	3.5	0	768	1113	376	0	0.49	0.23	0.2
0.19	0	40	0	1	29.4	14.4	6.1	7609	245	3531	120	0	0.39	0.16	0.2
0.19	10	0	0	1	22	14.4	4.8	6133	367	3102	180	0	0.4	0.18	0.2
0.19	0	0	0	1	18	12.2	0.6	0	1275	1265	624	1149	0.55	0.28	0.2
0.19	0	0	70	1	19	14.4	3.4	413	752	1256	368	0	0.48	0.23	0.2
0.19	0	0	70	1	16.2	12	0.7	848	1242	1428	608	1281	0.54	0.28	0.2
0.19	10	0	0	1	32.4	8.2	1.5	13067	792	3010	388	3050	0.55	0.32	0.2
0.19	0	40	0	1	38.7	6.5	0.9	20144	621	3749	304	3790	0.6	0.35	0.2
0.19	5	0	0	1	--	14.4	--	4333	523	2575	256	0	0.44	--	0.2
0.19	0	0	70	0.5	--	14.5	--	866	370	902	816	0	0.92	--	0.2
0.19	10	0	0	0.5	--	14.5	--	5933	159	2731	352	0	0.78	--	0.2
0.19	5	0	0	0.5	--	14.5	--	3700	199	1865	440	0	0.78	--	0.2
0.19	5	0	0	1	--	14.4	--	4333	523	2575	256	0	0.44	--	0.2
0.19	0	0	70	1.5	--	14.4	--	273	1300	1983	261	0	0.33	--	0.2
0.19	10	0	0	1.5	--	14.4	--	5800	551	3201	112	0	0.27	--	0.2
0.19	5	0	0	1.5	--	14.5	--	3900	748	2741	152	0	0.28	--	0.2
0.19	0	0	70	2	--	14.5	--	127	1765	2596	192	0	0.24	--	0.2
0.19	10	0	0	2	--	14.5	--	5333	698	3248	76	0	0.19	--	0.2
0.19	5	0	0	2	--	14.4	--	3733	993	2978	108	0	0.20	--	0.2
0.19	5	0	0	1	--	9.3	--	8133	989	2419	484	2542	0.53	--	0.2
0.19	0	10	0	1	--	14.5	--	0	168	1114	376	0	0.49	--	0.2
0.19	0	10	0	1	--	12.2	--	196	1266	1303	620	1179	0.55	--	0.2

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Dried October 1:														-	
Dried using unheated air														-	
0.16	0	0	0	1.5	11.8	14.5	-	0	650	2823	132	0	0.03	-	0.33
0.16	0	0	0	2	15.9	14.4	-	0	809	3348	88	0	0.02	-	0.33
0.16	0	0	0	1	-3.7	14.7	-	0	2206	11334	1080	0	0.08	-	0.33
0.16	0	0	0	2	5.9	13.6	-	0	4046	11271	440	467	0.04	-	0.33
0.19	0	0	0	2	10.1	14.4	-	0	3972	5709	432	0	0.13	-	0.33
														-	
Undried:														-	
0.16	0	0	0	0.5	-4.7	15.3	-	0	490	4583	1080	0	0.08	-	0.33
0.19	0	0	0	0.5	-4.6	17.8	-	0	490	2506	1080	0	0.31	-	0.33
0.19	0	0	0	1	-3.8	16.7	-	0	2206	6039	1080	0	0.26	-	0.33
0.19	0	0	0	1.5	-2.4	15.4	-	0	5320	9601	1080	0	0.20	-	0.33
0.19	0	0	70	1	-0.7	16.4	-	4096	2206	7422	1080	0	0.26	-	0.33
0.19	0	0	70	1.5	0.5	15.1	-	5204	5320	10589	1080	0	0.20	-	0.33
0.19	5	0	0	0.5	0.4	15.9	-	9032	490	2732	1080	0	0.37	-	0.33
0.19	0	0	70	0.5	-1.4	17.6	-	2252	490	3893	1080	0	0.33	-	0.33
0.19	0	0	50	0.5	5.4	15.5	-	10360	490	2553	1080	0	0.36	-	0.33
0.22	0	0	0	1	-3.8	19.1	-	0	2206	4765	1080	0	0.57	-	0.33
0.22	0	0	0	0.5	-4.6	20.5	-	0	490	1987	1080	0	0.64	-	0.33
0.22	0	0	0	1.5	-2.5	17.3	-	0	5320	7471	1080	0	0.49	-	0.33
0.22	0	0	70	1.5	0.4	17.1	-	5204	5320	8201	1080	0	0.50	-	0.33
0.22	0	0	70	1	-0.8	18.8	-	4096	2206	5861	1080	0	0.61	-	0.33
0.22	0	0	70	0.5	-1.4	20.3	-	2252	490	3109	1080	0	0.70	-	0.33
0.22	0	10	0	0.5	8	15.3	-	15196	490	1465	1080	0	0.77	-	0.33
0.22	5	0	0	0.5	0.4	18.4	-	9032	490	2283	1080	0	0.80	-	0.33
0.22	0	0	50	0.5	5.3	17.9	-	10360	490	2124	1080	0	0.79	-	0.33
0.22	0	0	0	2	-1.3	15.4	-	0	9931	9693	1080	0	0.38	-	0.33
														-	
Dried using supplemental heat														-	
0.16	5	0	0	1	11.7	14.5	-	1864	220	2019	108	0	0.03	-	0.33
0.16	0	10	0	1	8.4	14.5	-	1240	351	2458	172	0	0.03	-	0.33
0.16	5	0	0	0.5	10	14.5	-	3300	178	2112	392	0	0.06	-	0.33
0.16	0	0	50	0.5	9.8	14.5	-	3200	201	2267	444	0	0.07	-	0.33
0.16	0	10	0	0.5	9.3	14.5	-	3188	205	2292	452	0	0.07	-	0.33
0.16	0	0	70	1	-0.6	14.7	-	4096	2206	15344	1080	0	0.08	-	0.33
0.16	5	0	0	1	9.3	12.4	-	7932	964	3839	472	1097	0.06	-	0.33
0.16	0	10	0	1	8.8	12.7	-	8036	1087	4469	532	972	0.06	-	0.33
0.19	5	0	0	1.5	6.6	14.5	-	5100	985	2602	200	0	0.12	-	0.33
0.19	10	0	0	0.5	8.6	14.5	-	8264	223	1025	492	0	0.32	-	0.33
0.19	0	0	30	0.5	13.1	14.5	-	8696	205	971	452	0	0.31	-	0.33
0.19	5	0	0	1	13.9	14.5	-	6932	841	2581	412	0	0.18	-	0.33
0.19	0	10	0	1.5	9.2	14.5	-	5224	1477	3452	300	0	0.13	-	0.33
0.19	0	0	50	1.5	9.2	14.5	-	5056	1497	3460	304	0	0.13	-	0.33
0.19	0	0	50	1	8.2	14.5	-	5936	931	2632	456	0	0.18	-	0.33
0.19	0	10	0	1	8.6	14.5	-	6032	940	2668	460	0	0.18	-	0.33
0.19	0	10	0	0.5	7.1	14.5	-	10216	372	1613	820	0	0.31	-	0.33
0.19	5	0	0	1.5	12.3	11.9	-	11400	2226	3865	452	1293	0.14	-	0.33
0.19	0	10	0	1.5	8.8	12.3	-	10108	2561	4299	520	1111	0.14	-	0.33
0.19	0	0	50	1.5	9.2	12.6	-	11508	3034	5271	616	947	0.14	-	0.33
0.19	0	10	0	1	10	11.8	-	16404	1561	3377	764	1360	0.19	-	0.33
0.19	0	0	30	0.5	13.8	9.8	-	24708	490	1227	1080	2335	0.39	-	0.33
0.22	10	0	0	1	11.8	14.5	-	12400	752	1726	368	0	0.44	-	0.33
0.22	5	0	0	2	8.9	14.4	-	8000	2170	3077	236	0	0.26	-	0.33
0.22	5	0	0	1.5	8.9	14.4	-	9400	1832	2894	372	0	0.33	-	0.33

Dried October 1
Dried using supplemental heat (cont'd)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
0.22	0	0	30	0.5	12.3	14.5	-	15332	334	962	736	0	0.79	-	0.33
0.22	0	15	0	0.5	11	14.5	-	15644	363	1031	800	0	0.76	-	0.33
0.22	0	10	0	1.5	9.8	14.4	-	7404	2147	2984	436	0	0.32	-	0.33
0.22	0	0	50	1.5	9.4	14.4	-	7500	2147	2995	436	0	0.33	-	0.33
0.22	0	10	0	1	8.9	14.5	-	11264	1266	2402	620	0	0.44	-	0.33
0.22	0	10	0	2	8.7	14.5	-	6904	2942	3685	320	0	0.26	-	0.33
0.22	0	0	50	2	9.9	14.5	-	6604	3053	3754	332	0	0.26	-	0.33
0.22	10	0	0	0.5	6.1	14.5	-	18068	490	1368	1080	0	0.89	-	0.33
0.22	5	0	0	1	1.2	14.5	-	18068	2206	4114	1080	0	0.56	-	0.33
0.22	0	0	50	1	9	14.5	-	16828	2068	3825	1012	0	0.53	-	0.33
0.22	0	10	0	2	8.3	12.2	-	10372	4487	4412	488	1125	0.27	-	0.33
0.22	5	0	0	2	18.9	11.7	-	14264	3899	4192	424	1345	0.28	-	0.33
0.22	0	0	50	2	6.9	12.4	-	10104	4855	4717	528	1047	0.28	-	0.33
0.22	5	0	0	1.5	7.6	12.1	-	18100	3546	4324	720	1236	0.35	-	0.33
0.22	0	10	0	1.5	8.8	11.7	-	16416	3132	3753	636	1377	0.33	-	0.33
0.22	0	0	50	1.5	10.9	12.8	-	20312	4728	5867	960	858	0.35	-	0.33
0.22	0	10	0	1	10.8	11.3	-	23460	1937	2959	948	1553	0.47	-	0.33
0.22	10	0	0	1	12.1	10.4	-	24132	1471	2286	720	1978	0.50	-	0.33
0.22	0	0	70	2	1.3	14.9	-	6388	9931	10348	1080	0	0.37	-	0.33

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Drying date October 1															
0.19	0	40	0	1	24.6	14.4	6.3	9065	204	4112	100	0	0.2	0.08	0.33
0.19	10	0	0	1	10.6	14.5	4.1	7067	425	3623	208	0	0.17	0.07	0.33
0.19	0	0	0	2	10.1	14.4	0	0	3972	5709	432	0	0.13	0.05	0.33
0.19	0	0	50	1	8.2	14.5	2.2	5936	931	3861	456	0	0.18	0.07	0.33
0.19	10	0	0	1	11.4	10.1	1.5	17734	1078	4871	528	2163	0.21	0.11	0.33
0.19	0	40	0	1	38.9	5	1.6	31746	604	5150	296	4448	0.32	0.19	0.33
0.19	0	0	70	1.5	0.5	15.1	1.1	5207	5320	11350	1080	0	0.2	0.09	0.33
0.19	0	0	0	1	-3.8	16.7	2	0	2206	6039	1080	0	0.25	0.1	0.33
0.19	0	0	0	1.5	-2.4	15.4	1.8	0	5320	9601	1080	0	0.2	0.09	0.33
0.19	0	0	70	1	-0.7	16.4	1.7	4098	2206	8435	1080	0	0.26	0.11	0.33
0.19	0	0	70	0.5	--	17.6	--	2253	490	5210	1080	0	0.33	--	0.33
0.19	5	0	0	0.5	--	15.9	--	9034	490	6426	1080	0	0.37	--	0.33
0.19	0	0	70	1	--	16.4	--	4098	2206	8435	1080	0	0.26	--	0.33
0.19	0	0	70	1.5	--	15.1	--	5207	5320	11351	1080	0	0.20	--	0.33
0.19	10	0	0	1.5	--	14.4	--	6200	591	3421	120	0	0.12	--	0.33
0.19	0	0	70	2	--	14.5	--	1786	3788	6237	412	0	0.13	--	0.33
0.19	10	0	0	2	--	14.5	--	5867	772	3597	84	0	0.08	--	0.33
0.19	5	0	0	2	--	14.4	--	4267	1140	3384	124	0	0.09	--	0.33
0.19	5	0	0	1	--	11.7	--	15334	1871	5878	916	1423	0.21	--	0.33
0.19	0	10	0	2	--	14.5	--	3325	1876	4111	204	0	0.10	--	0.33
0.19	0	29	0	1	--	14.4	--	7613	433	3817	212	0	0.16	--	0.33
0.19	0	0	0	1	--	14.5	--	0	2043	2949	1000	0	0.27	--	0.33
0.19	0	0	70	1	--	14.5	--	2243	2002	3861	980	0	0.27	--	0.33
0.19	0	0	0	0.5	--	14.5	--	0	795	1155	1752	0	0.58	--	0.33
0.19	0	0	0	1.5	--	14.5	--	0	4175	6007	844	0	0.19	--	0.33
0.19	0	0	70	0.5	--	14.5	--	1802	712	1802	1568	0	0.53	--	0.33
0.19	0	0	70	1.5	--	14.5	--	3001	4078	7176	828	0	0.19	--	0.33
0.19	5	0	0	0.5	--	14.5	--	8267	448	4148	988	0	0.39	--	0.33
0.19	0	0	0	1	--	12.1	--	0	2762	2707	1352	1197	0.31	--	0.33
0.19	0	0	70	1	--	12.2	--	2729	2697	3441	1320	1182	0.31	--	0.33
0.19	0	10	0	1	--	11.8	--	16406	1561	5978	764	1360	0.19	--	0.33
0.19	0	20	0	0.5	--	14.5	--	9005	192	4107	425	0	0.31	--	0.33
0.19	0	20	0	1	--	14.4	--	7613	433	3817	212	0	0.16	--	0.33
0.19	0	20	0	1.5	--	14.4	--	5328	729	3261	148	0	0.11	--	0.33
0.19	0	20	0	2	--	14.5	--	4437	1029	3371	112	0	0.08	--	0.33

APPENDIX VIII

COMPARISONS OF EXPERIMENTAL TO SIMULATED MOISTURE

TABLE 27. Layer Moisture Contents for Run 1 in Bin C.

GRAIN HEIGHT ft (m)	DAY NO. 226 Exp. Sim.	228 Exp. Sim.	230 Exp. Sim.	232 Exp. Sim.	234 Exp. Sim.	236 Exp. Sim.	238 Exp. Sim.	240 Exp. Sim.
16 (4.9)	18.1 18.1	17.5 17.6	17.6 17.7	17.6 17.5	17.5 17.5	17.5 17.4	17.5 16.2	17.5 15.2
13 (4.0)	18.2 18.1	17.4 17.6	17.4 17.7	17.4 17.4	17.1 17.1	17.4 16.4	15.7 14.5	15.7 13.9
10 (3.0)	18.1 18.1	17.5 17.5	17.2 17.6	17.6 16.9	17.4 15.8	17.7 14.7	15.2 13.4	15.2 13.3
7 (2.1)	17.9 18.1	17.6 17.4	17.7 16.9	17.9 15.2	16.3 14.1	15.1 13.7	13.2 12.8	13.2 13.1
4 (1.2)	17.9 18.1	17.5 16.4	16.6 15.2	15.3 13.4	13.9 13.2	13.2 13.1	12.5 12.4	12.5 12.9
1 (0.3)	17.9 18.1	14.4 13.1	13.5 12.6	13.1 12.4	12.9 11.9	11.4 11.1	11.6 12.3	11.6 12.6
AVG.	18.0 18.1	17.0 16.6	16.7 16.3	16.5 15.5	15.9 14.9	15.4 14.4	14.3 13.6	14.3 13.5

EXP. = Experimental
SIM. = Simulated

TABLE 28. Average Bin Moisture Contents.

RUN	BIN	DAY NO. 226 Exp. Sim.	227 Exp. Sim.	228 Exp. Sim.	229 Exp. Sim.	230 Exp. Sim.	231 Exp. Sim.	232 Exp. Sim.	233 Exp. Sim.	234 Exp. Sim.	235 Exp. Sim.
1 (Aug.)	A 104°F (40°C) Inlet Air Temperature	17.6 17.6	16.0 16.4	15.1 14.9	14.0 13.8	13.5 12.7	12.7 11.4	11.9 10.4	10.5 9.3	8.9 8.3	7.7 7.9
	B 86°F (30°C) Inlet Air Temperature	17.9 17.9	17.4 16.9	16.6 16.0	16.2 15.3	15.7 14.6	15.4 13.8	14.9 12.6	14.2 11.9	13.9 11.1	13.6 10.4
	C Standard Bin (Normal Weather)	18.0 18.0	17.3 17.3	16.9 16.8	16.8 16.6	16.5 16.3	16.4 16.1	16.3 15.5	15.6 15.3	15.5 15.0	15.5 14.7
		DAY NO. 262 Exp. Sim.	263 Exp. Sim.	268 Exp. Sim.	271 Exp. Sim.	274 Exp. Sim.	277 Exp. Sim.				
2 (Sept.)	A Add Heat if Humidity > 70%	16.9 16.9	15.9 16.0	15.2 15.1	14.1 14.6	13.7 14.2	13.3 14.2				
	B Add 18°F (10°C) Above Ambient Temperature	17.2 17.3	16.3 16.1	15.6 14.3	14.4 12.8	13.6 11.4	12.8 11.3				
	C Standard Bin (Humid Weather)	17.1 17.1	16.8 16.8	16.8 16.8	16.6 16.8	16.3 16.4	16.2 16.9				
		DAY NO. 290 Exp. Sim.	293 Exp. Sim.	296 Exp. Sim.	299 Exp. Sim.	302 Exp. Sim.	305 Exp. Sim.				
3 (Oct.)	A Add Heat if Humidity > 70%	17.2 17.3	16.2 15.9	15.7 14.8	14.6 13.9	13.9 13.0	13.8 13.0				
	B Add 18°F (10°C) Above Ambient Temperature	17.2 17.1	15.9 14.4	15.2 12.4	13.4 10.6	12.3 9.7	12.3 10.2				
	C Standard Bin (Cold Weather)	17.4 17.3	16.5 16.1	16.6 16.0	16.1 15.8	16.3 15.5	16.0 15.5				

EXP. = Experimental
SIM. = Simulated